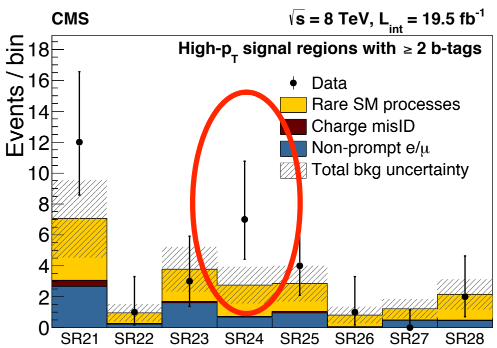
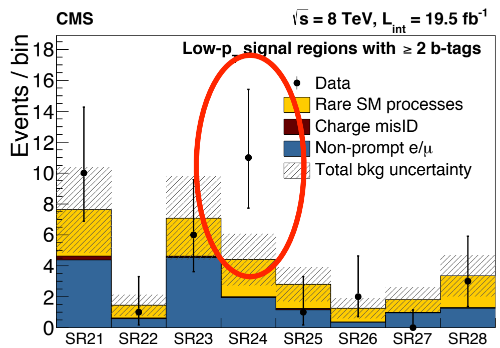
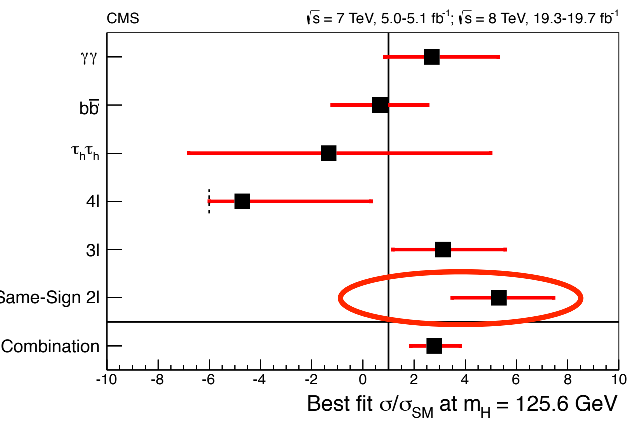
Same Sign Lepton Excesses



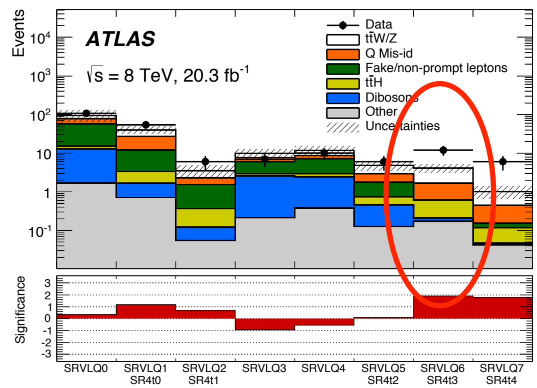


SR1b $_{1bin}$	Total	ee	$e\mu$	$\mu\mu$
Observed events	10	6	4	0
Total expected background events	4.7 ± 2.1	1.4 ± 0.8	2.1 ± 1.1	1.2 ± 0.4
Components of the background				
$t\bar{t}V$, $t\bar{t}H$, tZ and $t\bar{t}t\bar{t}$	2.5 ± 1.7	0.6 ± 0.3	1.2 ± 1.0	0.7 ± 0.3
Dibosons and tribosons	0.9 ± 0.4	0.10 ± 0.04	0.3 ± 0.1	0.5 ± 0.3
Fake leptons	$0.8^{+1.2}_{-0.8}$	$0.4^{+0.7}_{-0.4}$	$0.4^{+0.5}_{-0.4}$	< 0.1
Charge-flip electrons	0.5 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	–
$p(s = 0)$	0.07	0.01	0.18	0.50

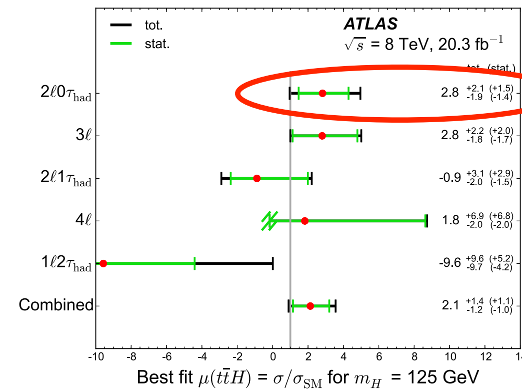
CMS (SUSY), http://arxiv.org/abs/1311.6736 (24 signal regions in paper) ATLAS (SUSY), http://arxiv.org/abs/1404.2500 (5 signal regions in paper)



CMS (ttH), http://arxiv.org/abs/1408.1682



ATLAS (TT), http://arxiv.org/abs/1504.04605



ATLAS (ttH), http://arxiv.org/abs/1506.05988

The ATLAS analyses are correlated, and same for CMS

So, ~2 analyses and excesses are < 3 σ

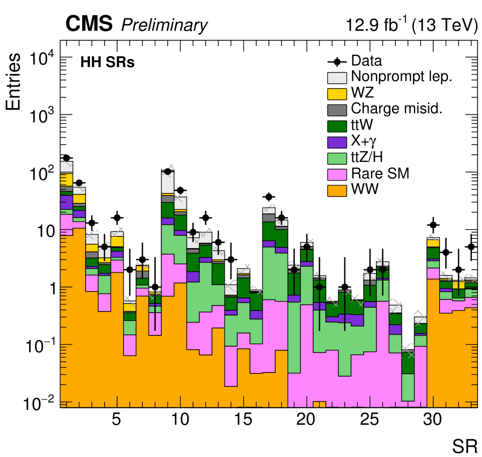
Worth keeping an eye on? Sure.

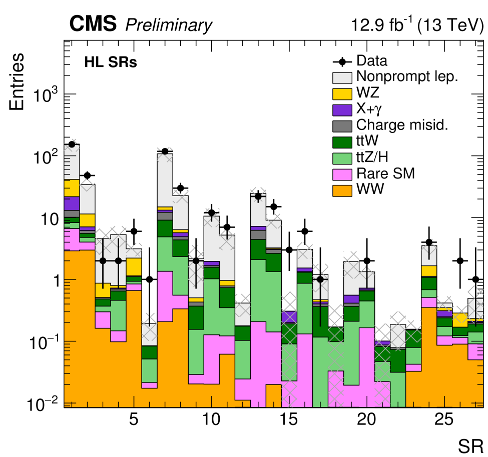
13 TeV

ATLAS-CONF-2016-037

	SR3L1	SR3L2	SR0b1	SR0b2	SR1b
Observed	6	2	5	0	12
Total SM background	6.1 ± 2.2	1.2 ± 0.5	8.8 ± 2.9	1.6 ± 0.8	11.4 ± 2.8
$t\bar{t}Z$	0.69 ± 0.25	0.10 ± 0.04	0.45 ± 0.18	0.10 ± 0.04	1.6 ± 0.6
$t\bar{t}W$	0.09 ± 0.04	0.02 ± 0.01	0.45 ± 0.17	0.13 ± 0.06	2.0 ± 0.7
Diboson	4.2 ± 2.0	0.7 ± 0.4	3.7 ± 1.9	0.7 ± 0.5	0.5 ± 0.4
Rare	0.8 ± 0.4	0.21 ± 0.13	0.8 ± 0.4	0.18 ± 0.12	2.7 ± 0.9
Fake/non-prompt leptons	0.29 ± 0.29	0.15 ± 0.15	2.9 ± 2.0	0.4 ± 0.5	3.3 ± 2.1
Charge-flip	–	–	0.50 ± 0.09	0.08 ± 0.03	1.43 ± 0.19

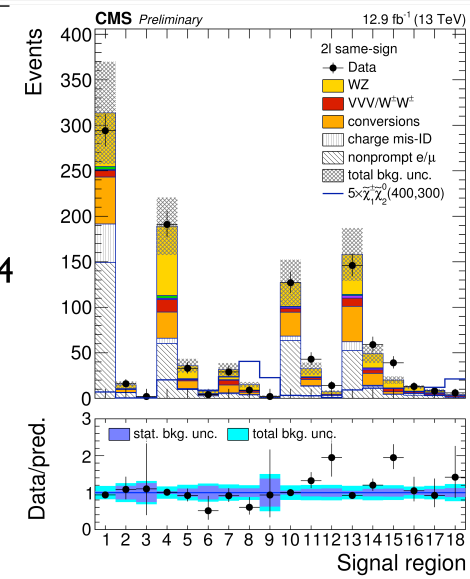
	SR3b	SR1b-GG	SR1b-DD	SR3b-DD
Observed	2	2	12	4
Total SM background	1.6 ± 0.6	1.7 ± 0.5	12.0 ± 2.7	1.9 ± 0.8
$t\bar{t}Z$	0.19 ± 0.07	0.26 ± 0.08	2.8 ± 0.9	0.30 ± 0.10
$t\bar{t}W$	0.17 ± 0.06	0.33 ± 0.11	1.8 ± 0.6	0.18 ± 0.07
Diboson	< 0.1	0.08 ± 0.19	0.6 ± 0.4	< 0.1
Rare	0.89 ± 0.31	0.64 ± 0.34	2.6 ± 1.3	0.8 ± 0.4
Fake/non-prompt leptons	0.2 ± 0.5	0.21 ± 0.33	2.5 ± 1.7	0.5 ± 0.6
Charge-flip	0.14 ± 0.03	0.18 ± 0.07	1.74 ± 0.22	0.14 ± 0.03





CMS-PAS-SUS-16-020

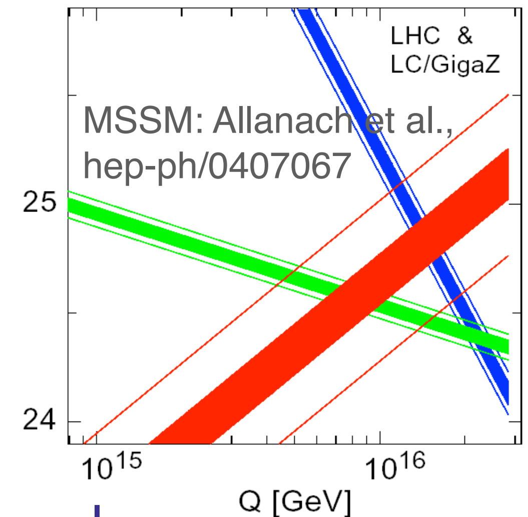
CMS-PAS-SUS-16-024



Not much there….

Not SUSY?

- SUSY theories (and others with full or partial set of SM-partners) have a number of attractive features
  - "Explanation" for low Higgs mass (and sometimes EWSB)
  - Gauge coupling unification (often)
  - Dark matter candidate (if introduce a new parity, natural in UED, ~ad-hoc in SUSY)
  - No new interactions (often)



- But answering those questions comes at a large cost
  - Many new particles, with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

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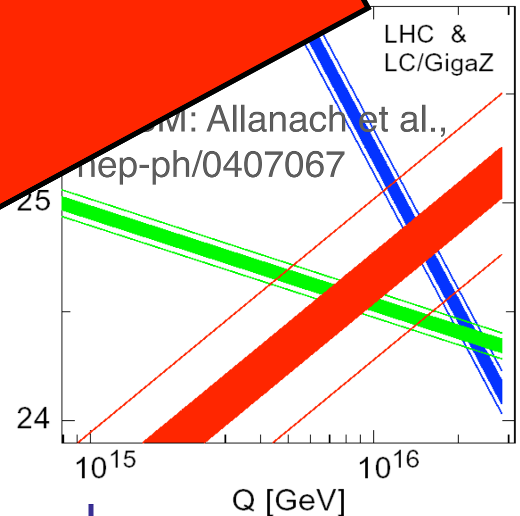


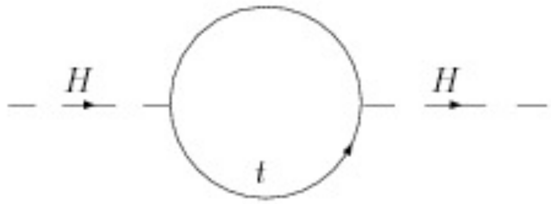
- But a[...] questions comes at a large cos[...]
  - Ma[...]w particles, with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

Dinosaurs on Venus?

Less Ambitious

Giving up on Dark Matter

- Electroweak-scale WIMPs fit the data well
  - But maybe hard/impossible to produce at colliders
- Or dark matter not WIMPs at all
- Back to problem #1:



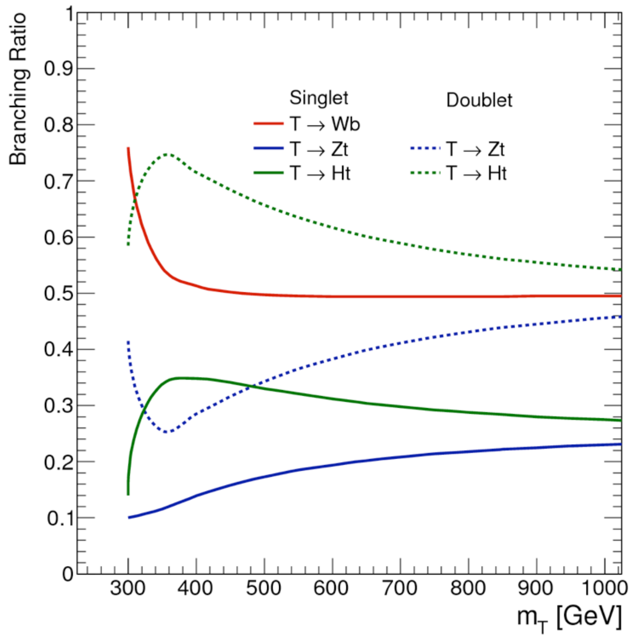
$$\longrightarrow \frac{3}{16\pi^2} y_t^2 E^2$$

➡ Top partner!

Singlets, Doublets, ...

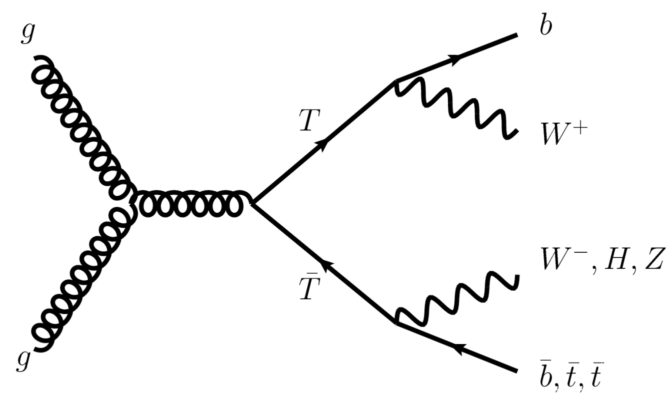
❖ Vector-like top partners (still fermions) less constrained by flavor....

- Opens up decay modes
- Top partner partners:
  - $X^{5/3}$
  - ...



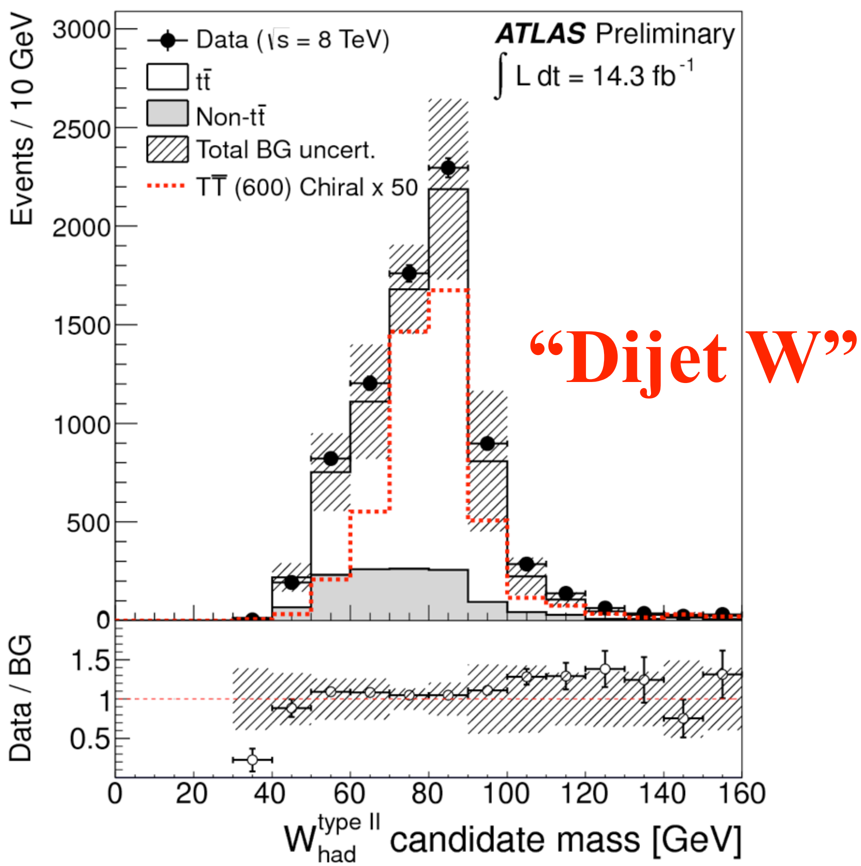
❖ Rich set of signatures

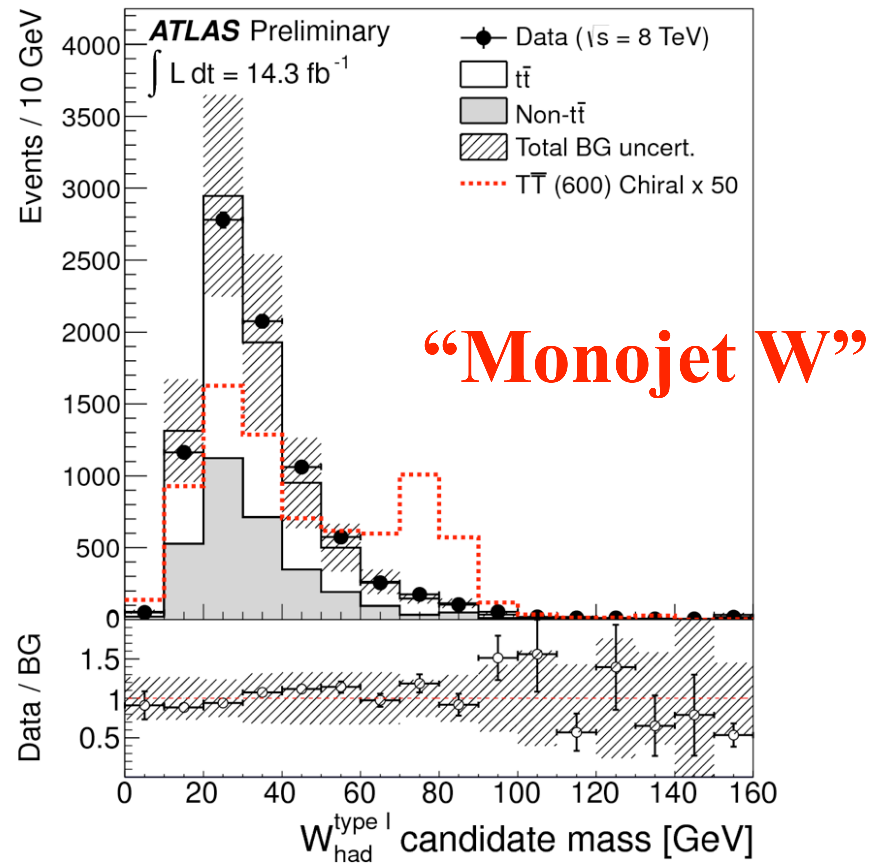
- Just no huge MET
- At least not systematically…



W's Can Be Light

- T→Wb with m_T ~600 GeV
  - ➡ W will be boosted, and if decays hadronically → single jet

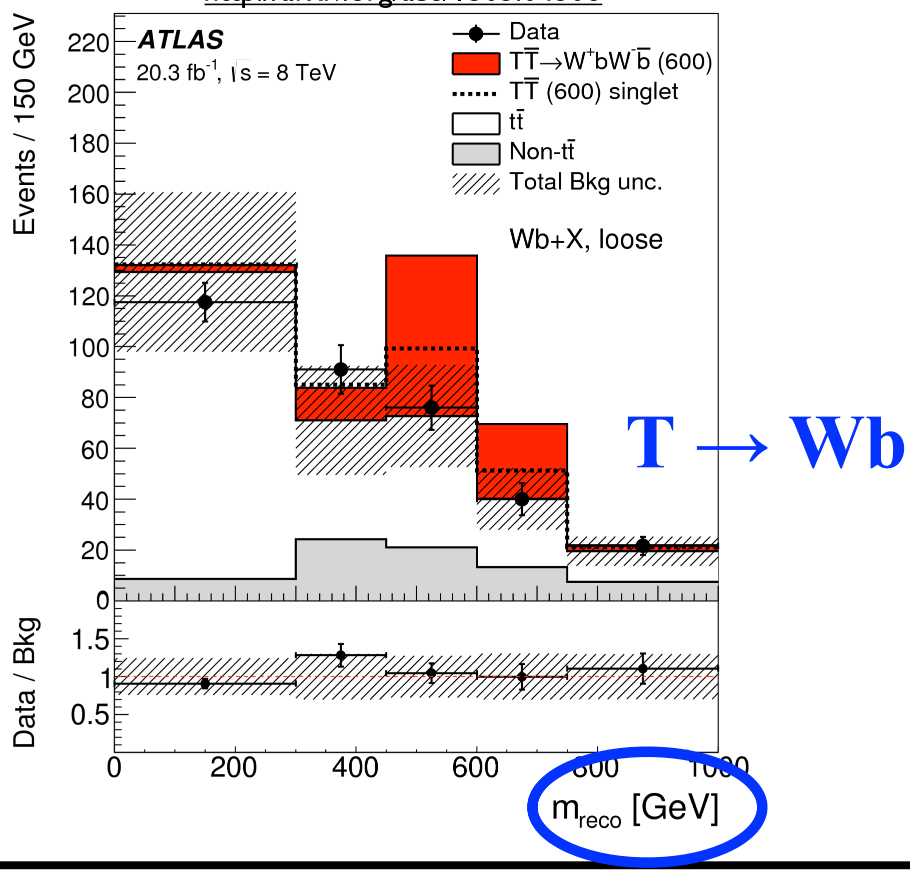




Wb versus Ht

- ❖ $T \rightarrow Wb$ yields the same final state as $t \rightarrow Wb$
  - Need to discriminate, e.g. reconstruct m_T

http://arxiv.org/abs/1505.04306



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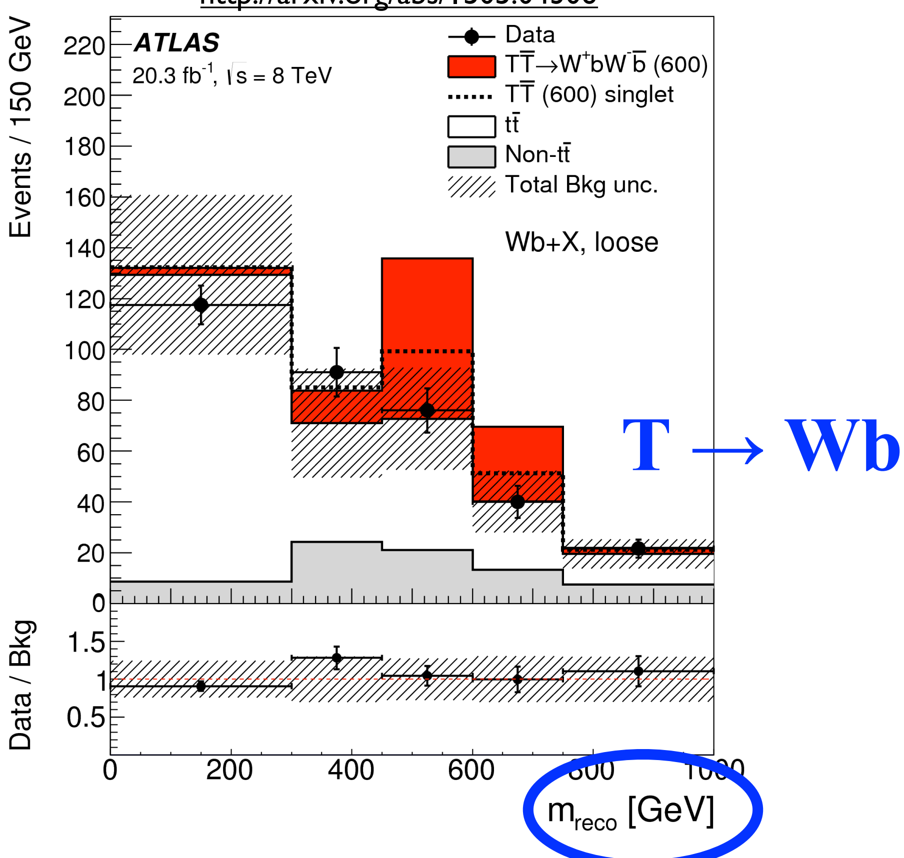

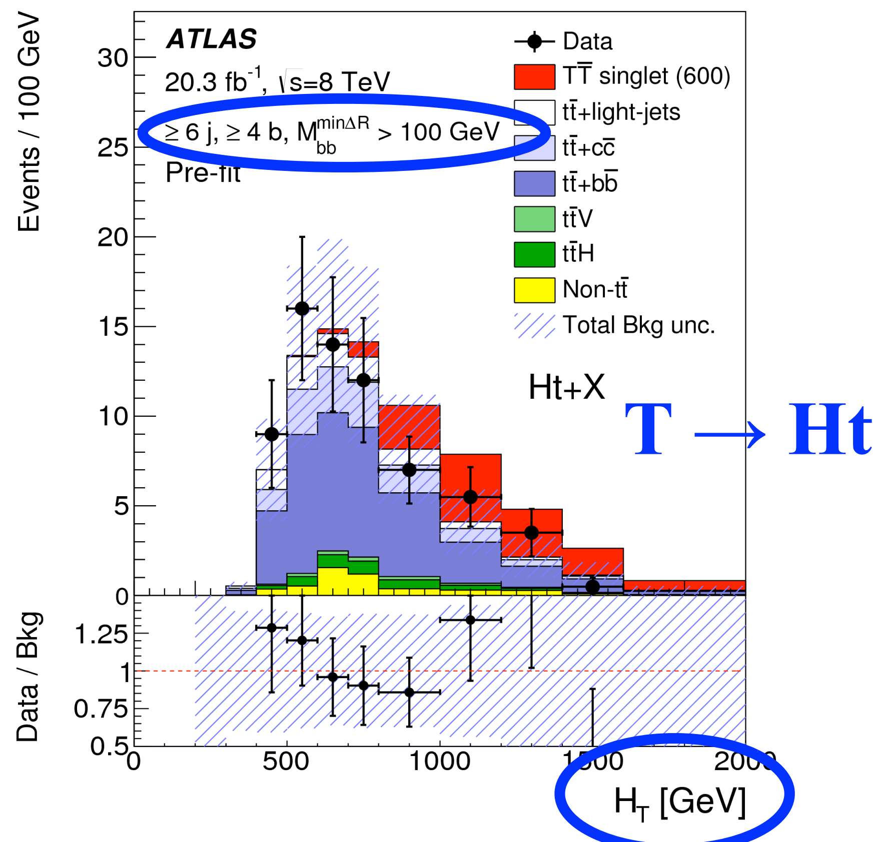

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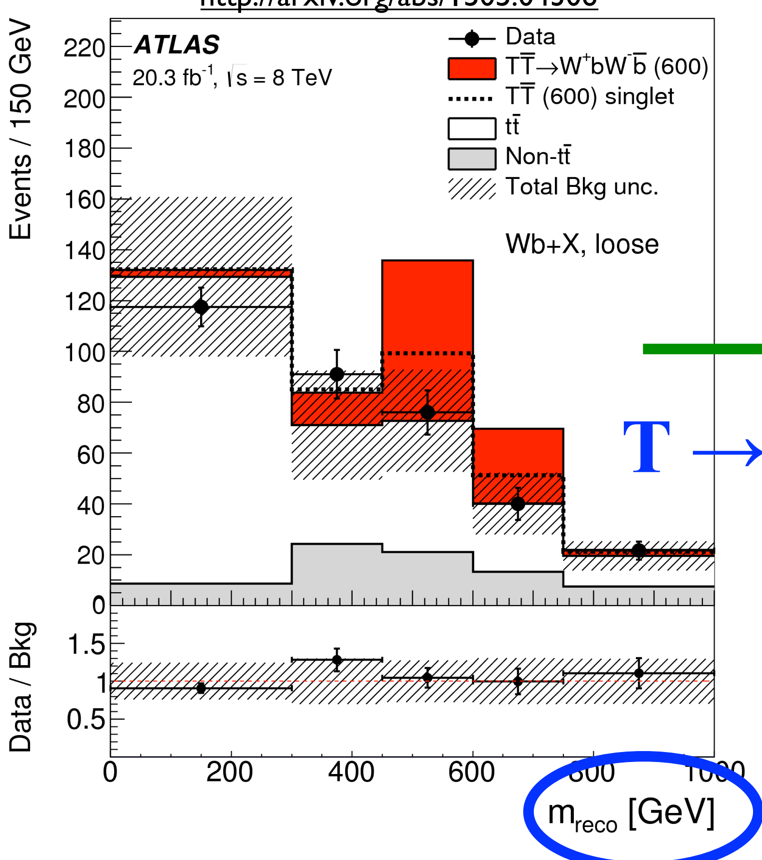

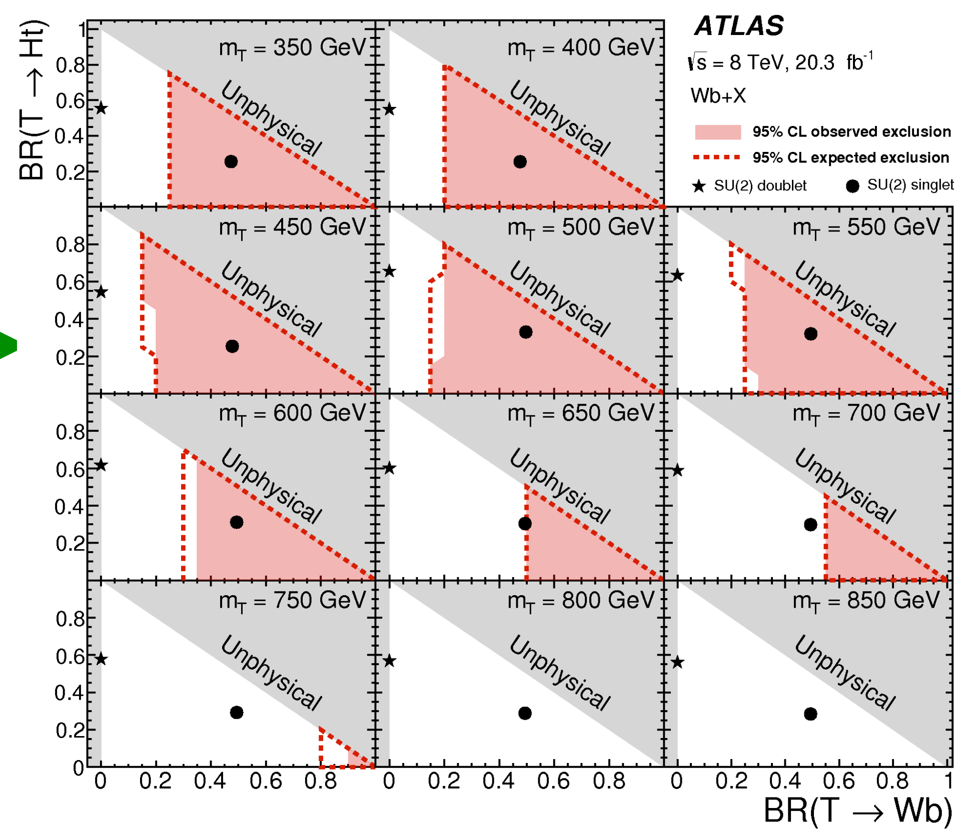

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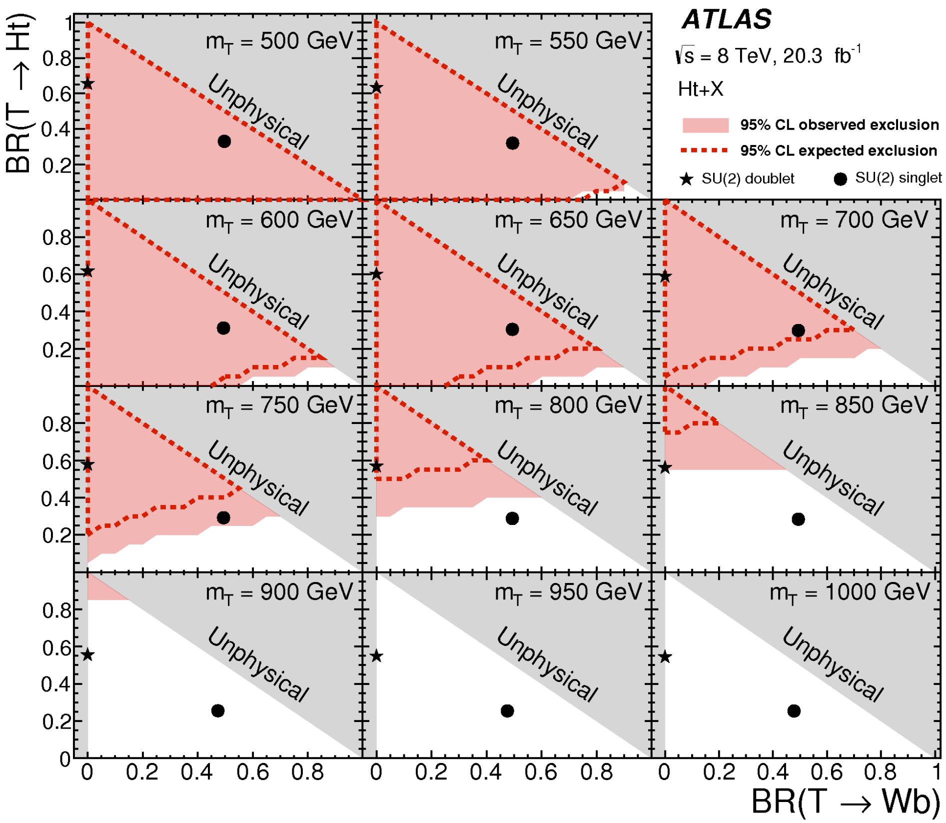

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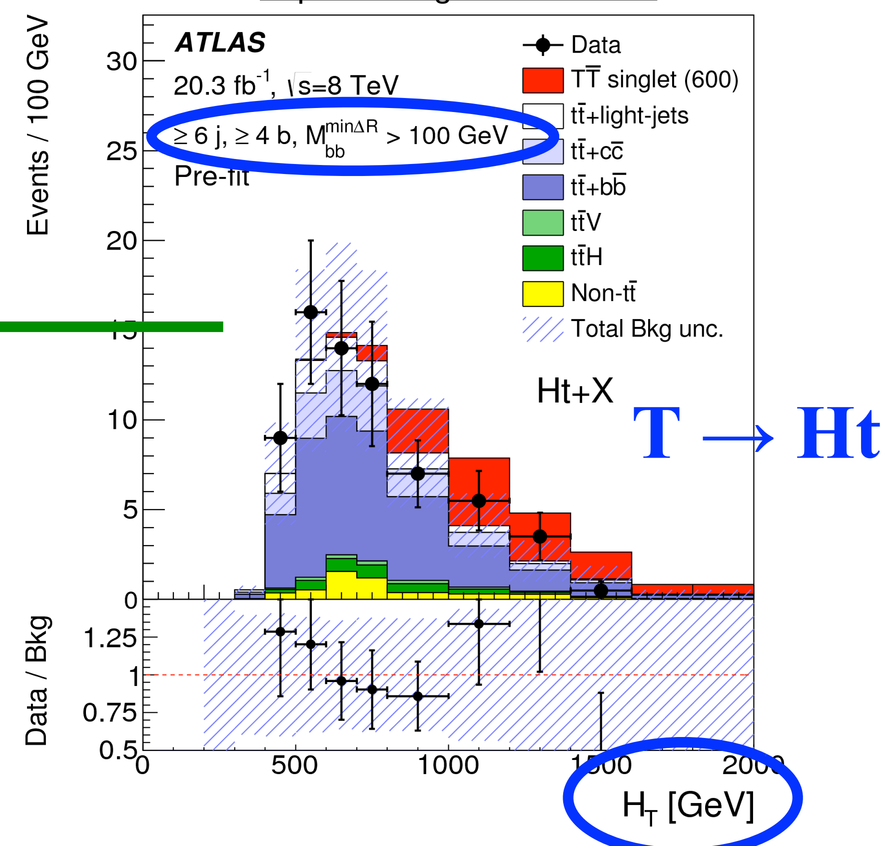
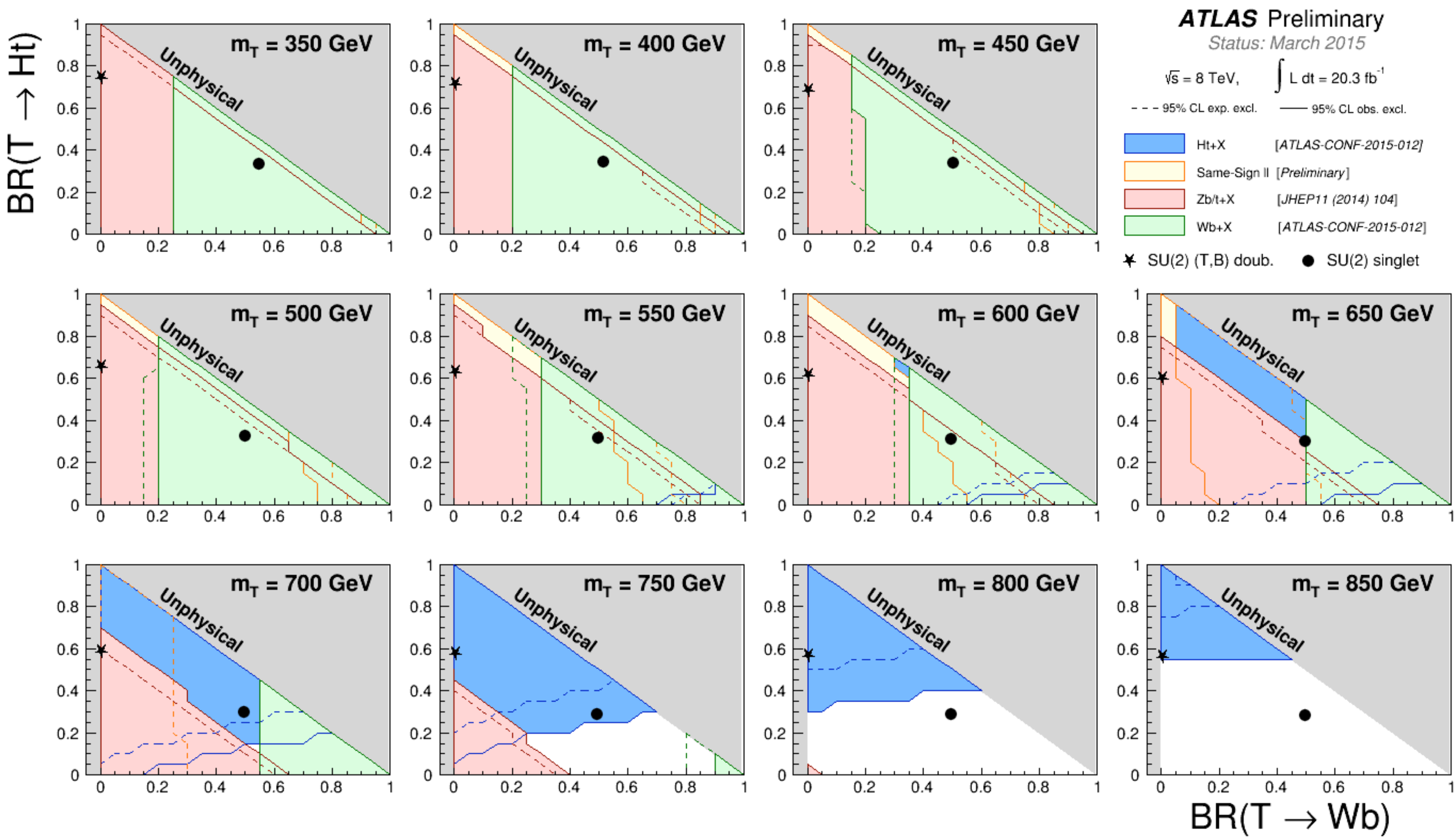
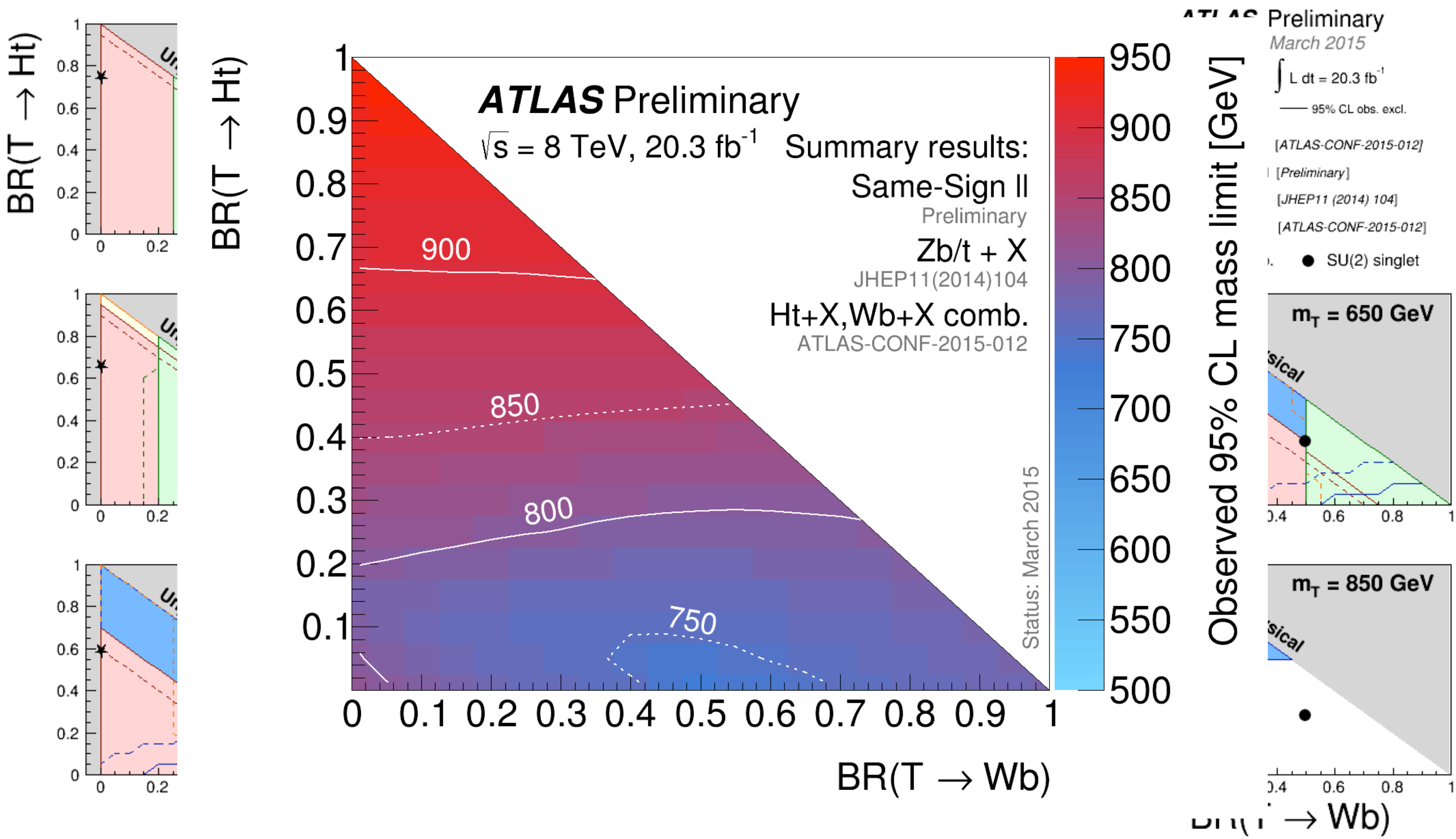


All Together Now



Presented Differently



Anecdotes From the Field (II)

- It turns out these targeted searches maybe weren't useful (or all that well optimized)
  - "In particular, we find that missing energy searches designed for superparticle production, supply superior sensitivity for vector-like quarks than the dedicated new quark searches themselves"
    - Biekötter, Hewett et al. arXiv:1608.01312
  - "Owing to the much higher production cross-sections of heavy top quarks as compared to stops, masses up to $m_T \approx 850$ GeV can be excluded from the Run 1 stop searches"
    - Kraml et al. arXiv:1607.02050
- The moral of the story…

Also

- Somewhat simplistic: other new particles?

T, B	qH	ql^+l^- Z, LQ	$q\ E_{\mathrm{T}}^{\mathrm{miss}}$ Z, LQ	$ql^+\nu$ W, LQ	qqq Z/W	qW^+W^- H, Q	qZH Q	qHH Q	qW^+Z Q	qW^+H Q
qH	D	-								
ql^+l^-	A	A	-							
$q\ E_{\mathrm{T}}^{\mathrm{miss}}$	C	A	C	-						
$ql^-\nu$	D	A	C	A	-					
qqq	E	A	B/C	A/B	A/E	-				
qW^+W^-	B	A	B	A	A/B	A	-			
qZH	A	A	A	A	A	A	A	-		
qHH	D	A	C	B	B/C	B	A	C	-	
qW^-Z	A	A	A	A	A	A	A	A	A	-
qW^-H	D	A	C	A	A/C	A	A	C	A	B

Table 1: A: ≥ 2 leptons ($Z, \geq 3\,W, l+W$). B: 1 lepton ($2W$). C: $E_{\mathrm{T}}^{\mathrm{miss}}$. D: VH, HH, tH. E: $W/H/t$+jets, all jets

X, Y	$ql^+\nu$ W, LQ	qqq W	qW^+Z Q	qW^+H Q
$ql^-\nu$	A	-		
qqq	A/B	A/E	-	
qW^-Z	A	A	A	-
qW^-H	A	D	A	B

Table 2: A: ≥ 2 leptons ($Z, \geq 3\,W, l+W$). B: 1 lepton ($2W$). C: $E_{\mathrm{T}}^{\mathrm{miss}}$. D: VH, HH, tH. E: $W/H/t$+jets, all jets

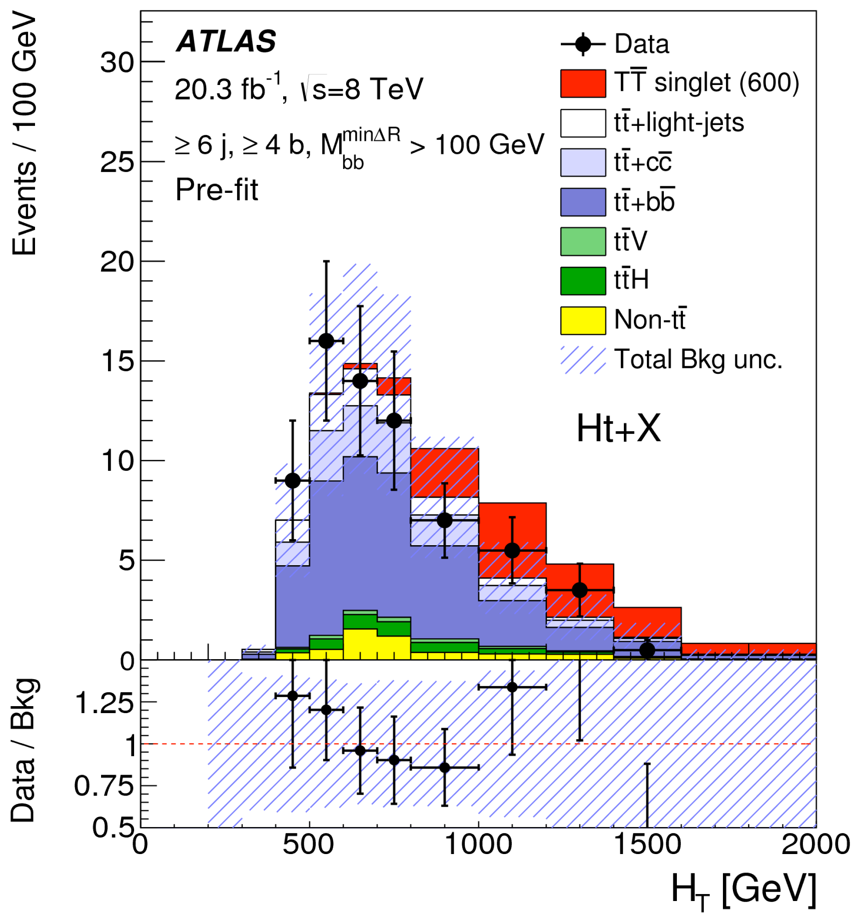
G Cacciapaglia, GB
in Les Houches 2015

Uncertainties

Systematic Uncertainties

- Statistical uncertainties are easy: with limited number of events (and experiments), precision on a measurement is limited
- Systematic uncertainties vastly more complex
  - Example: measure a cross-section: $\sigma = \frac{N_{\text{events}}}{\mathrm{L} A \epsilon}$
  - L is the integrated luminosity, A the acceptance, ε the efficiency
    - Statistical uncertainty comes from N_{events}
    - Systematic uncertainties arise from limited knowledge of L, A and ε
      - L is estimated from Van der Meer scans
      - A typically depends on parton distribution functions
      - efficiency is a convolution of many experimental uncertainties

Example

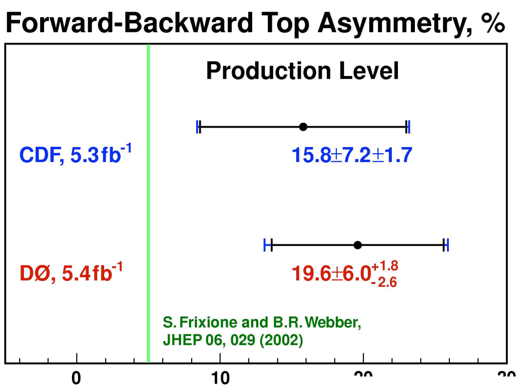


- ❖ H_T is the sum of scalar energies of jets, leptons,…
  - If the jet energy scale is different between data and MC, comparison is wrong
  - If the jet energy scale dependence on jet energy is wrong, distort shape
  - etc.
- ❖ But how do I determine the jet energy scale uncertainty?
  - testbeams (single pions)
  - dijet balance
  - γ/Z+jet balance
  - …
- ❖ What about the MC generation itself?

Simulation

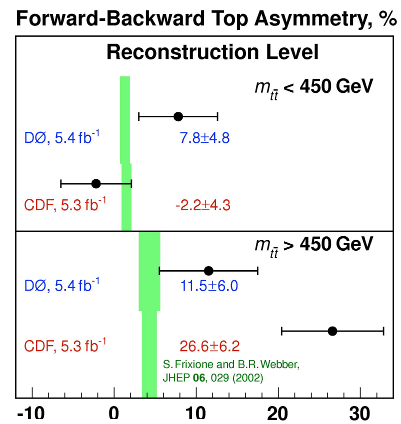
Anecdotes From the Field (III)

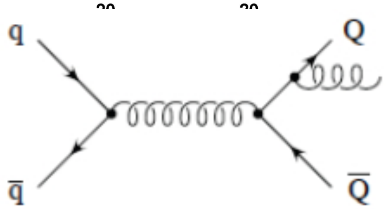
- $t\bar{t}$ charge asymmetry at the Tevatron
  - At Feynman diagram level, NLO effect (Tevatron is proton-anti-proton collider)



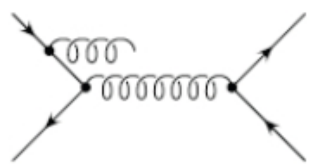
http://arxiv.org/abs/1107.4995

Ca. 2010, big fuss: much larger than SM!

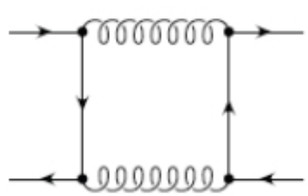




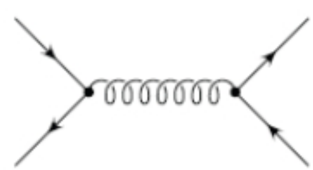
(a) Final state gluon bremsstrahlung FSR



(b) Initial state gluon bremsstrahlung ISR



(c) double virtual gluon exchange



(d) Born diagram

Anecdotes From the Field (III)

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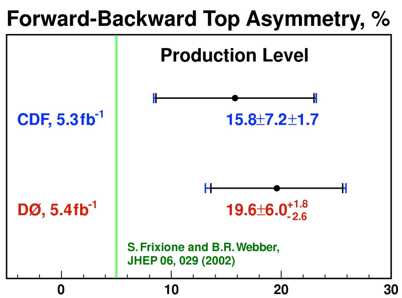
  - At Feynman diagram level, NLO effect (Tevatron is proton-anti-proton collider)



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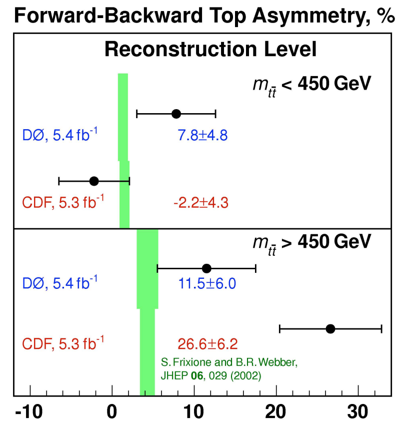
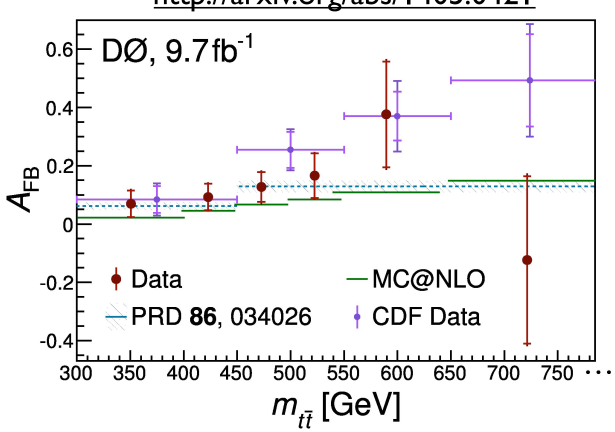


  - In real life, already exists at ~LO!
    - Shown it is there in Pythia: parton shower, recoils! Skands et al: http://arxiv.org/abs/1205.1466

http://arxiv.org/abs/1405.0421



    - Many scales in events Brodsky, Wu https://arxiv.org/abs/1205.1232

(My) current conclusion: no BSM physics here: just reality vs Feynman diagrams

About Generators…

- We use four kinds of Monte Carlo generators
  - "Calculators" (often NNLO) do not actually generate events, they just calculate some (limited) distributions, like W p_T
  - Traditional 2 → 2 generators: LO, e.g. $q\bar{q} \to WZ$
    - Include parton shower, i.e. QCD radiation, and hadronization to jets
    - pythia and herwig
  - "Matrix Element" 2 → n (n < 9): LO, e.g. $q\bar{q} \to e\nu jjjj$
    - Necessary to generate events with multiple hard jets
    - Require matching to parton shower to avoid double counting
  - NLOwPS 2 → n generators: include NLO corrections
    - I.e. in a sense they are 2 → n <u>with</u> virtual corrections

Correction Factors

❖ Of course, always limitations, so “K-factors” needed

- Different ones for heavy flavor etc..... (DØ) convention to avoid confusion....

• K-factor is purely theoretical, and denotes a (N)NLO/LO ratio of cross sections;

• K’-factor is also theoretical, and denotes a (N)NLO/LL ratio of cross sections. According to Steve, ALPGEN cross sections are Leading Log;

• S-factor is empirical, and comes on top of K or K’ to bring MC in agreement with data. MC should be initially normalized to luminosity, and all correction (a.k.a. scale) factors should be applied (trigger, ID...);

• HF-factor is, in principle, theoretical, but in practice only theory inspired. It tells you by how much heavy flavor production should be increased, on top of K or K’, and possibly S;

• S_HF-factor is empirical, and comes on top of K or K’, S, and HF, to bring MC in agreement with data, after b-tagging.

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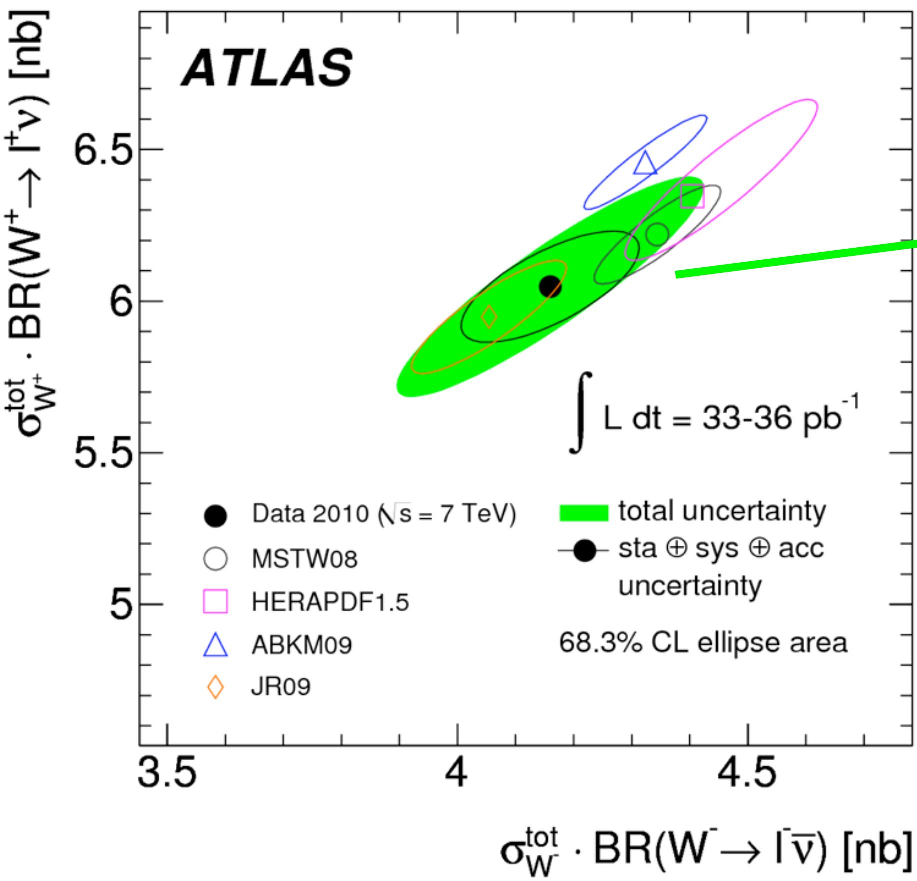
- S_HF-factor is empirical, and comes on top of K or K', S, and HF, to bring MC in agreement with data, after b-tagging.

In addition to W/Z PT reweighting

Sometimes Physics Helps

- At the LHC, produce more W^+ than W^-
  - Can exploit that to normalize W+jets

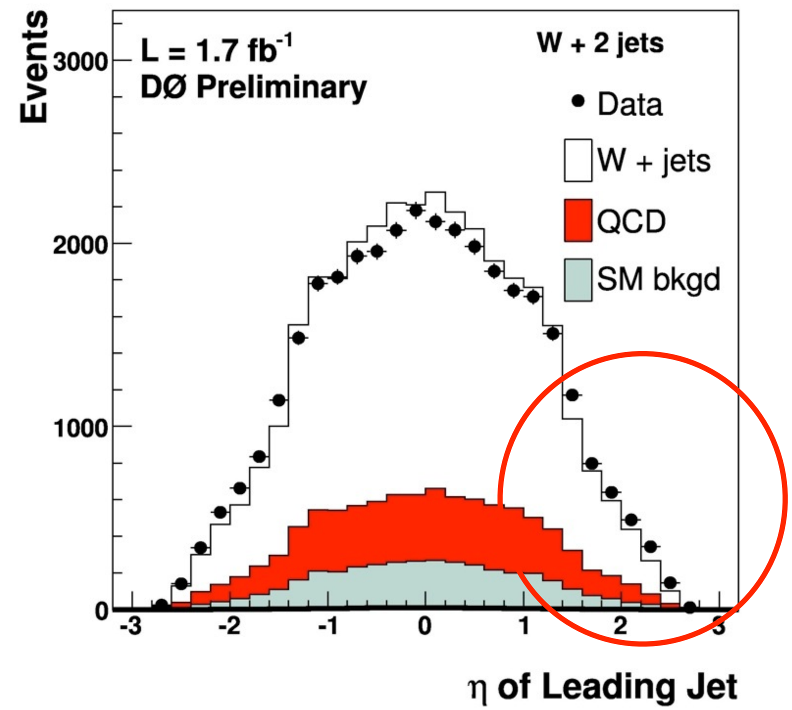


$$(N_{W^+} + N_{W^-})^{\text{exp}} = \left(\frac{r_{\text{MC}}+1}{r_{\text{MC}}-1}\right)(N_{W^+} - N_{W^-})^{\text{data}}$$

But what about shape??

Anecdotes From the Field (IV)

- Pile-up events ("minimum bias") do produce jets



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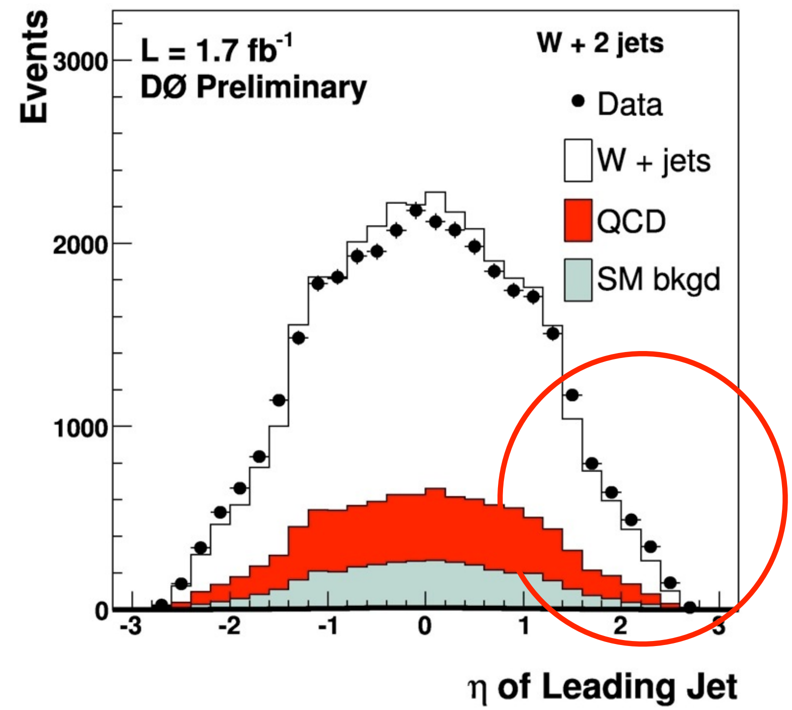
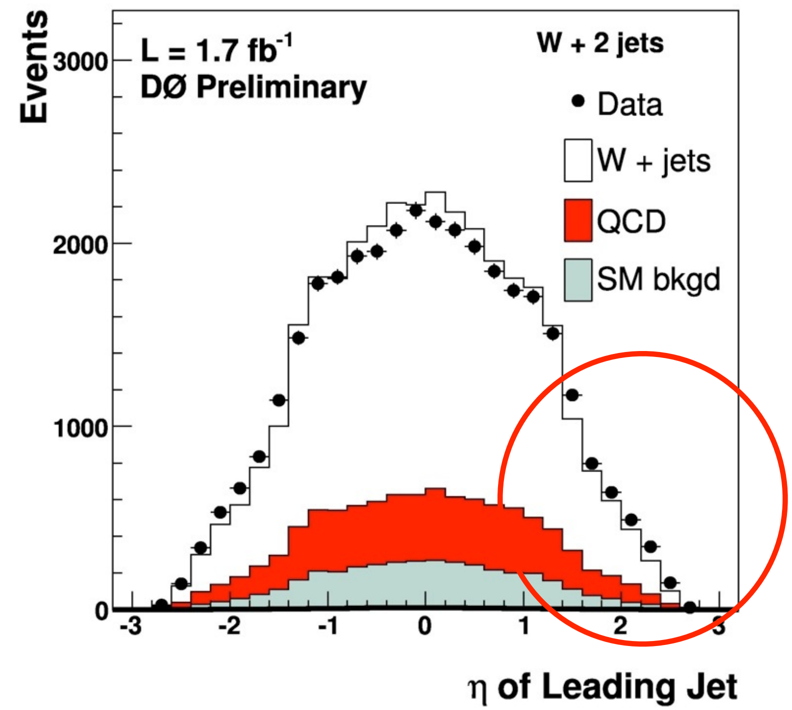
  - High η excess disappeared!



Anecdotes From the Field (IV)

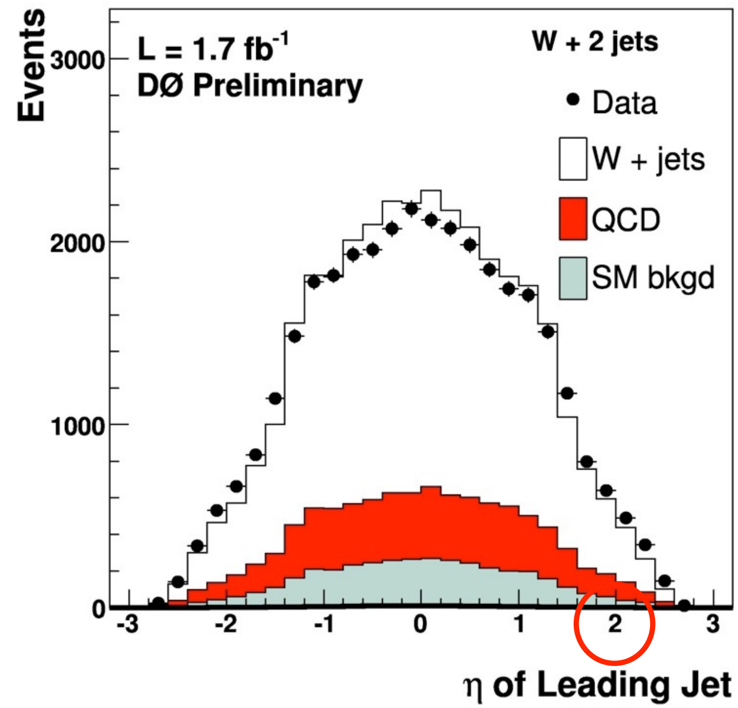
❖ Pile-up events ("minimum bias") do produce jets

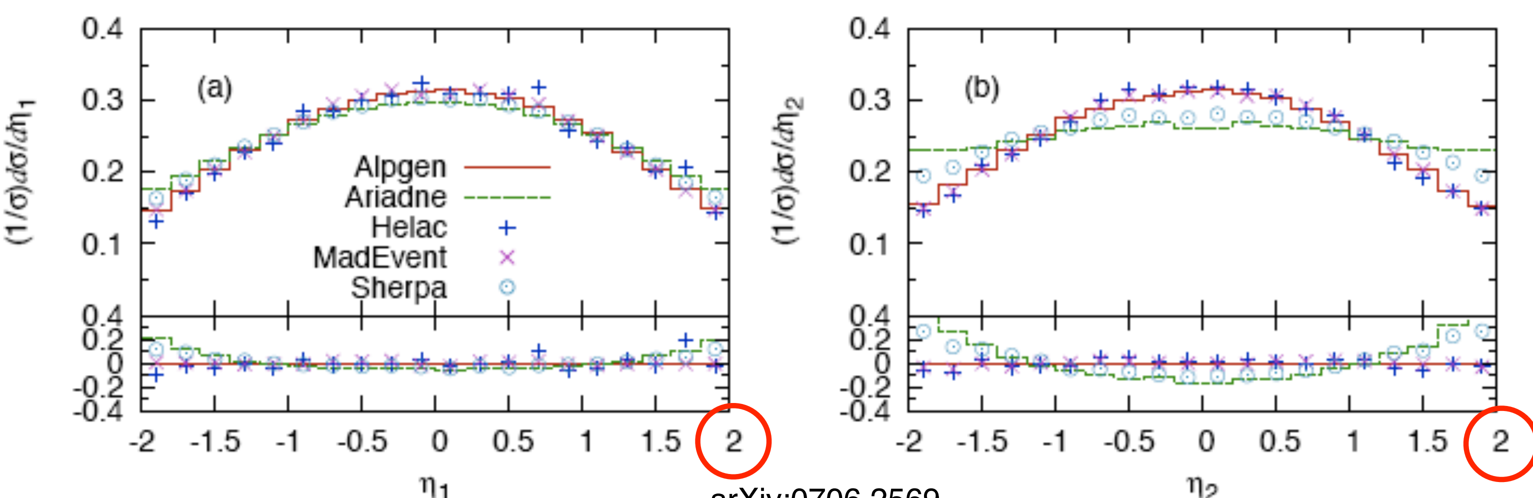
- At high ℒ, require that tracks pointing to jets originate from same vertex as lepton
- High η excess disappeared!
- Eta-dependence of jet-vertex match turns out to have shape very very similar to excess
- After correcting for this, excess was back....



So...

- After all K/K'/S/HF-factors and boson p_T reweighing:
- Similar angular differences between generators: reweigh alpgen to sherpa





arXiv:0706.2569

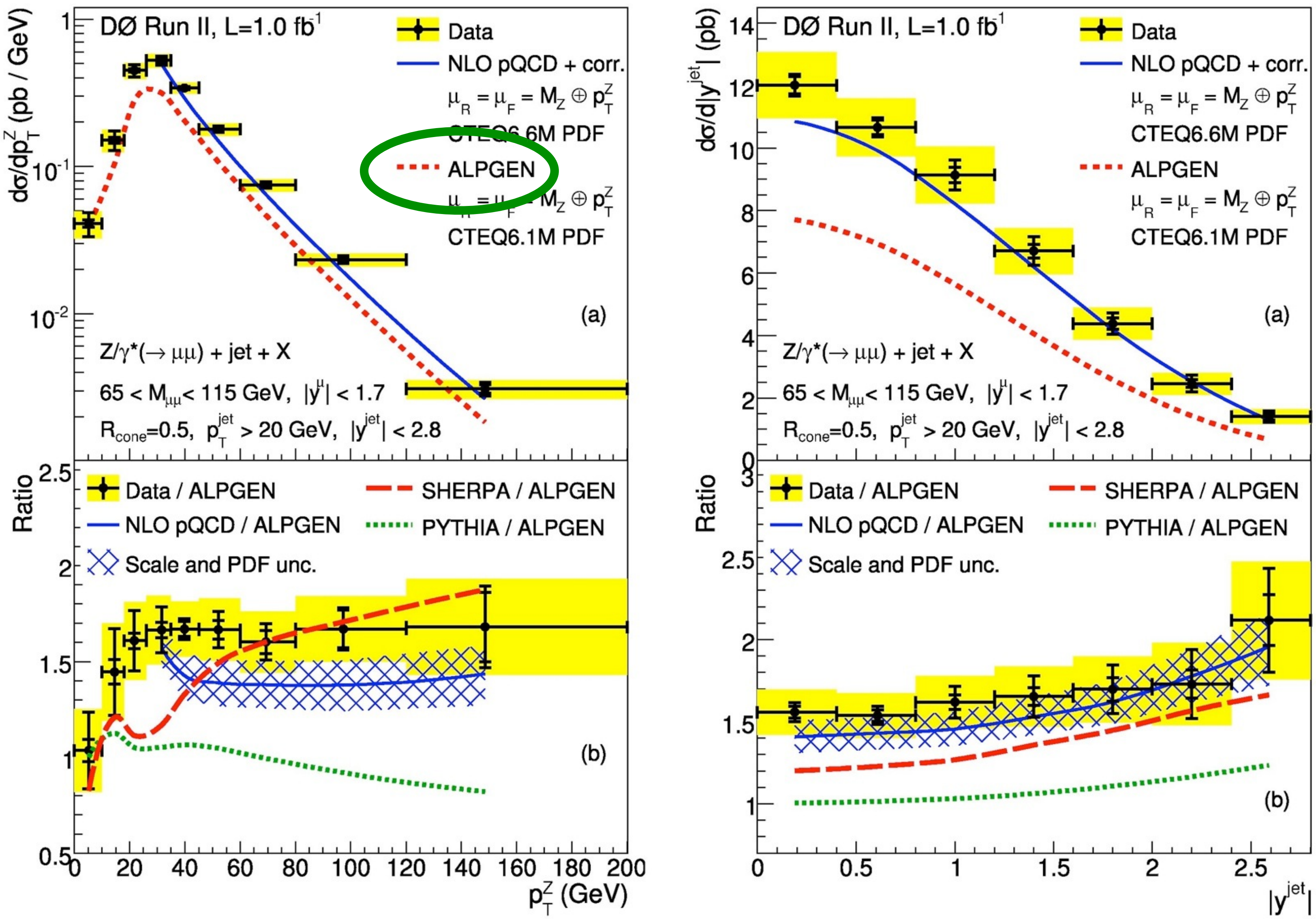
Alpgen, MadEvent, Helac with MLM, Sherpa and Ariadne with CKKW matching

Z (→ ℓℓ) + jets

- Can get a clean sample, check if our simulation reproduces the data

⇒ yes, with ~expected deviations

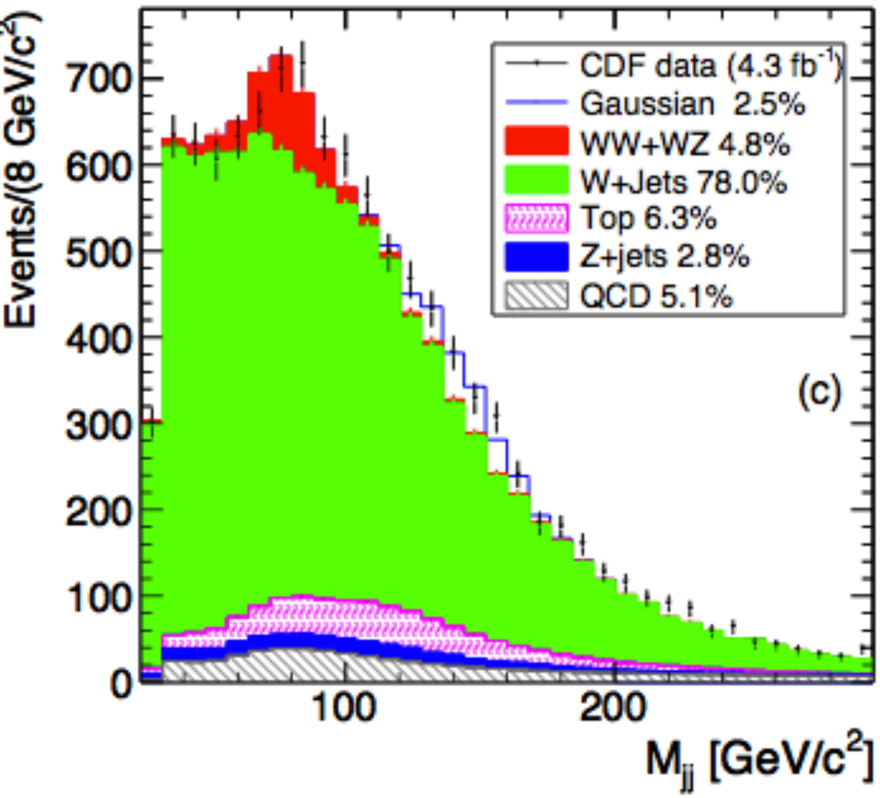
Need reweighing of MC

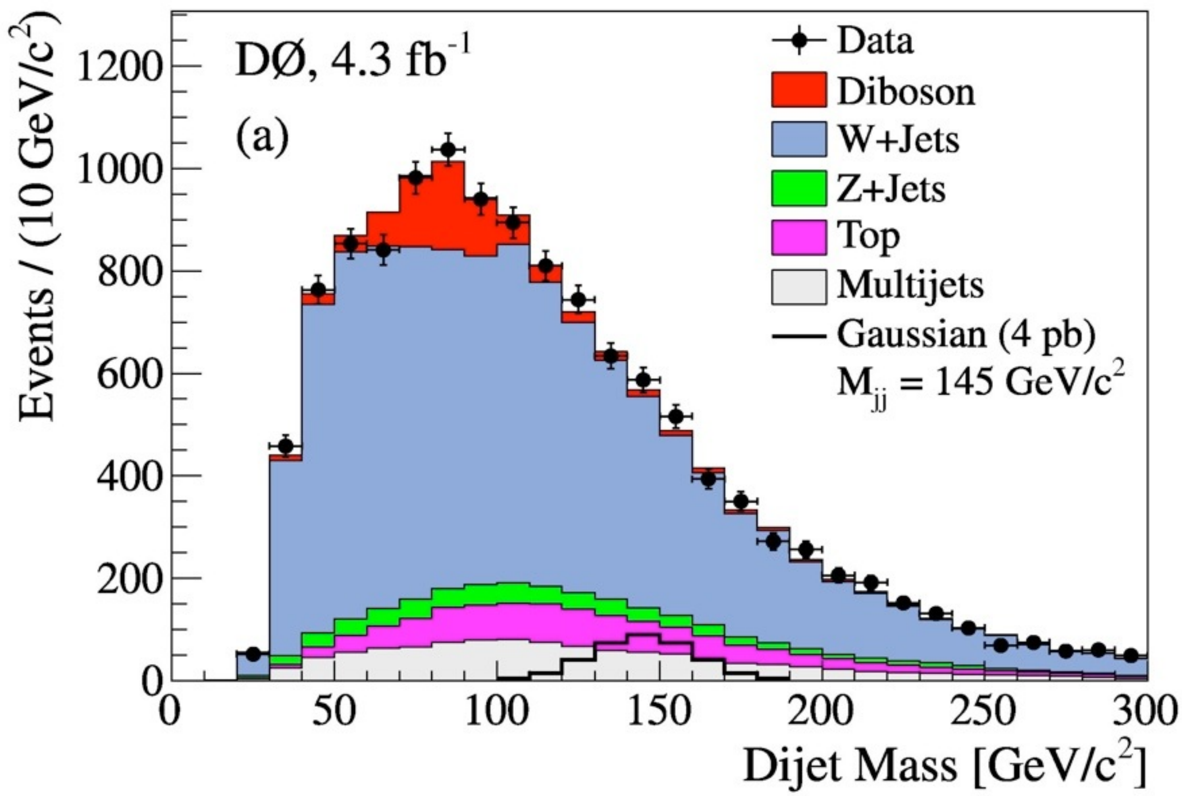


Anecdotes From the Field (V)

- Searched for WW/WZ in $\ell\nu jj$

Phys.Rev.Lett.106:171801





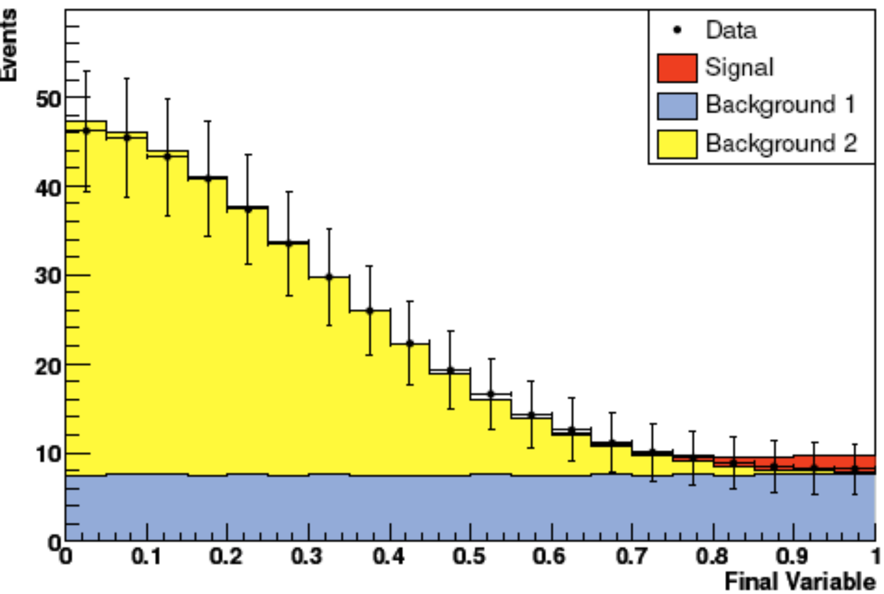
- The background here is not SM, it is uncorrected alpgen!!
  - But this is not the issue.....

Systematics Profiling

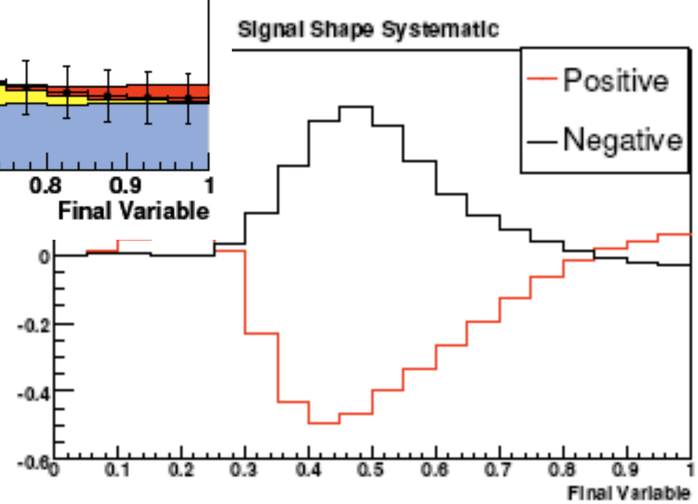
- Systematic uncertainties are propagated through the full analysis chain to the discriminating distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet/lepton/photon reconstruction efficiency, energy scale and resolution, p_T distributions, background models), others only normalization (lepton reconstruction efficiencies and momentum calibration, background normalizations, theoretical cross-sections and luminosity)
  - Systematic uncertainties are treated as nuisance parameters when fitting signal+background to the data
    - I.e. modify signal and background shape
    - Can be fixed, or allowed to change

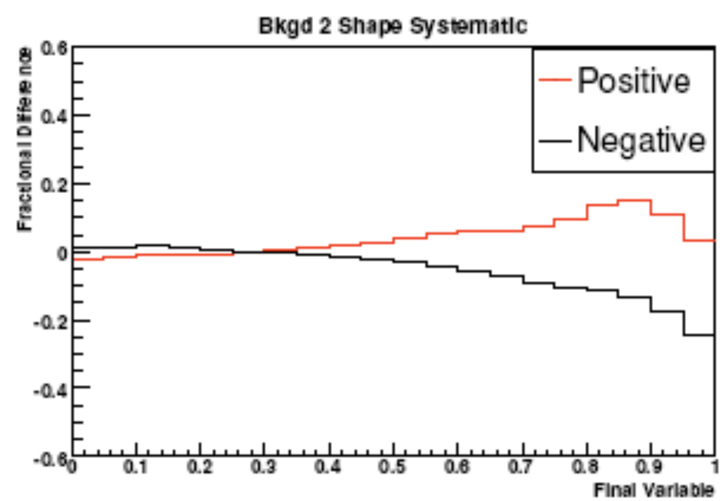
Systematics Profiling

- Nuisance parameters tend to be correlated, but not 100%, among backgrounds
  - Can affect rates, shapes, or both (in any distribution), and often asymmetric and non-gaussian



Toy Example (W. Fisher)

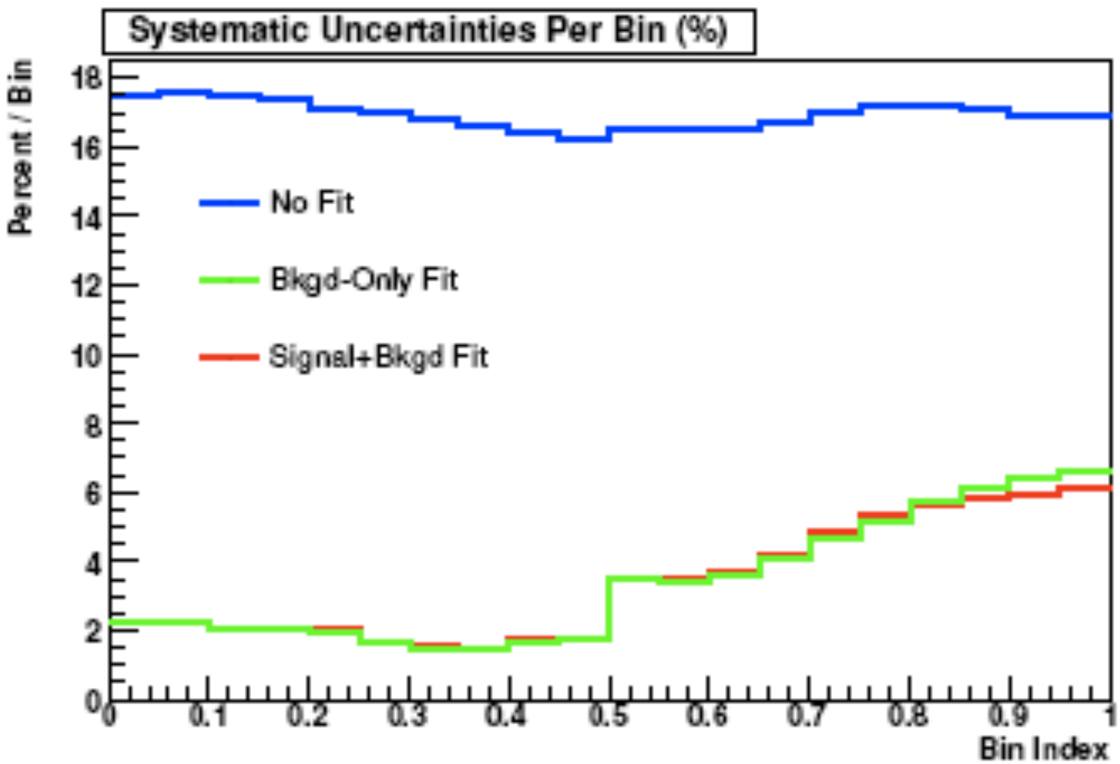




- Generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
  - Variations in background (& S+B) prediction
    - Compare results to data using log-likelihood ratio
- We can maximize likelihood ratio as a function of nuisance parameters → constrain them
  - I.e. use full shape of distribution(s) to see which background uncertainties are over/underestimated
    - Of course limited to size of statistical fluctuations
  - Can remove bins with large S/B if needed
    - Mostly important if uncertainties lead to similar shape distortions
  - Want enough background-rich phase space in fit!
    - Even include control regions

❖ Test example:

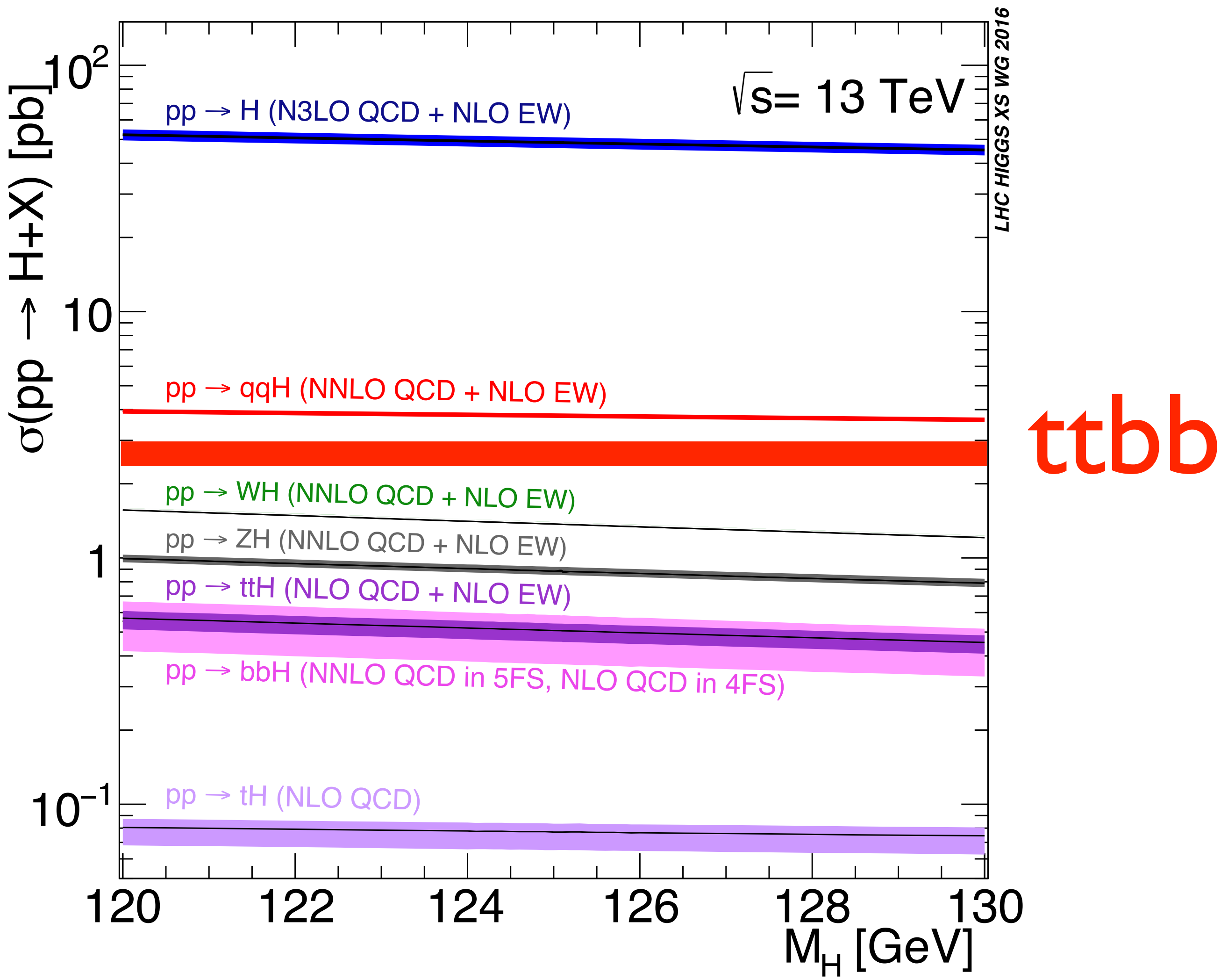
- Data constructed to disagree with background-only hypothesis (wrong estimates for background uncertainties)
- But to agree with background-only better than signal+ background
    - Improvement quite spectacular (by construction in example)



ttH

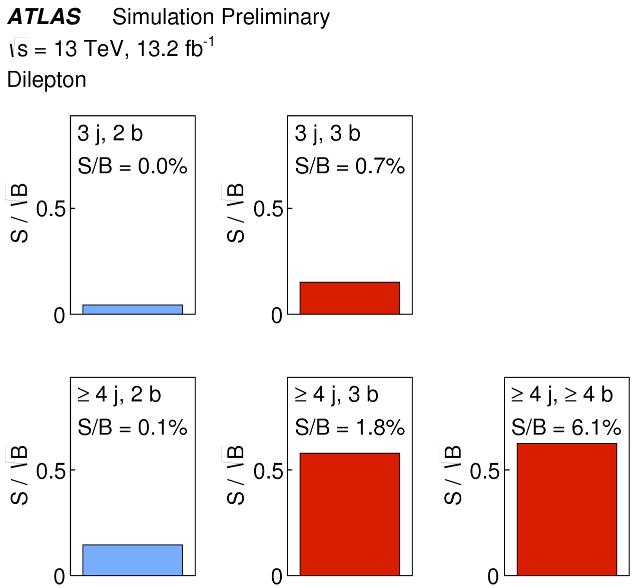
- ttH important measurement and discovery channel
  - If m_H had been smaller, no $H \rightarrow \gamma\gamma$, at 14 TeV S/B better for ttH than VH
  - Direct probe of t-H coupling
- Studied pre-data and looked good, but ttbb only known at LO at that time…
- In 2009, Bredenstein, Denner, Dittmaier and Pozzorini published ttbb@NLO (JHEP 1003 (2010) 021 and earlier)
  - ttbb twice as high as expected
  - At higher Higgs p_T, significant shape distortions
  - Would ttH be observable at all?
  - How can we understand ttbb with sufficient accuracy?

Production

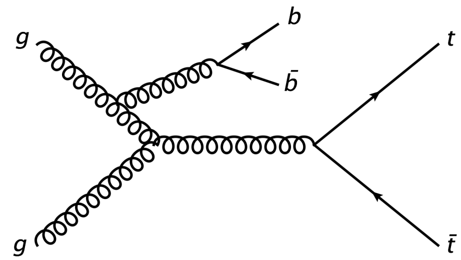


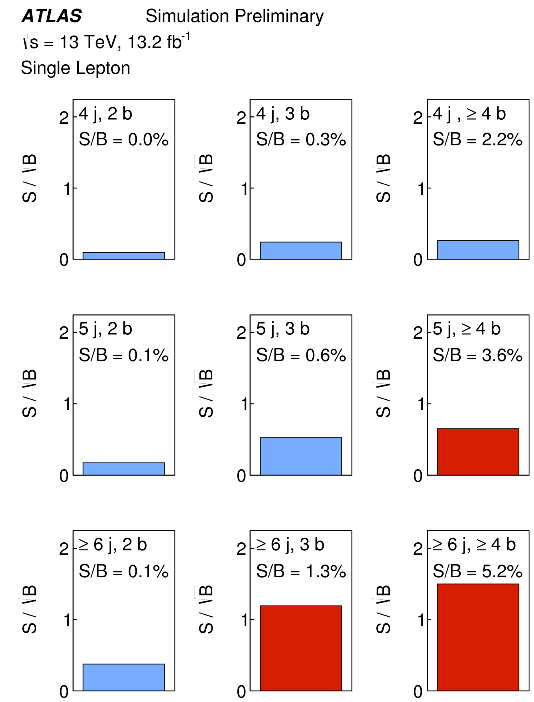
13 fb^{-1}: ~7000 ttH events, 4200 ttH, H → bb

Decay

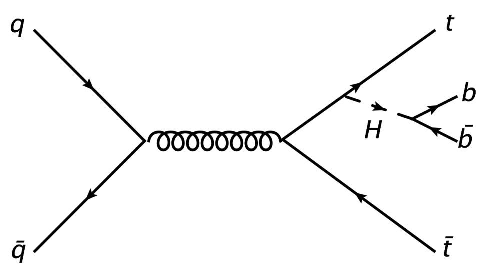


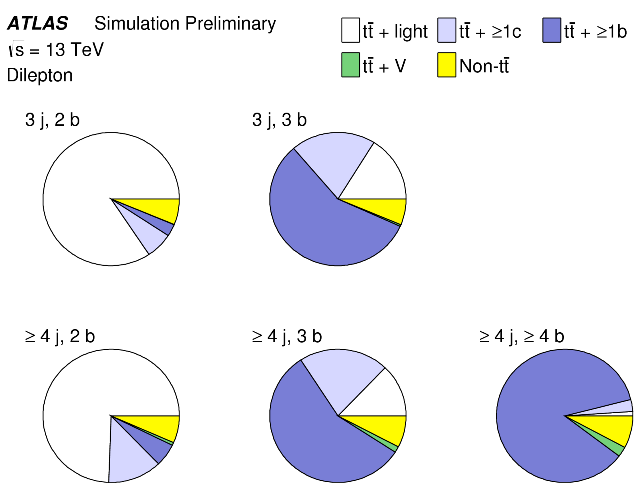
Control Regions

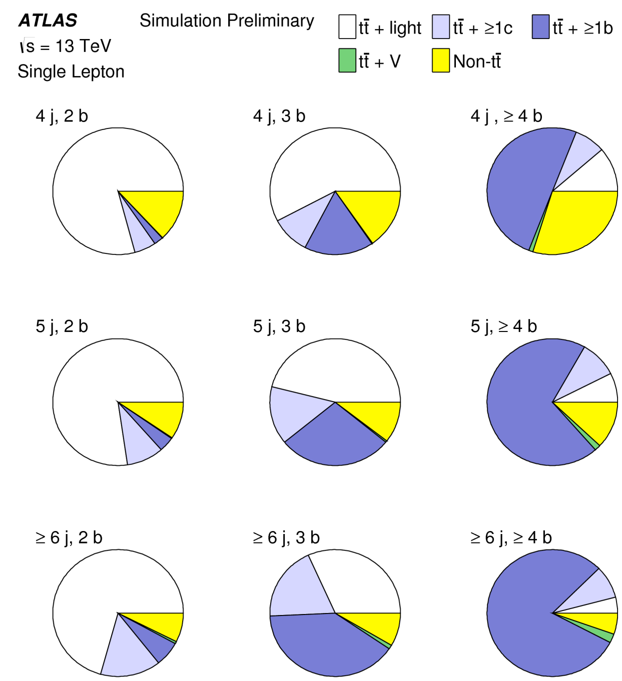




Signal Regions



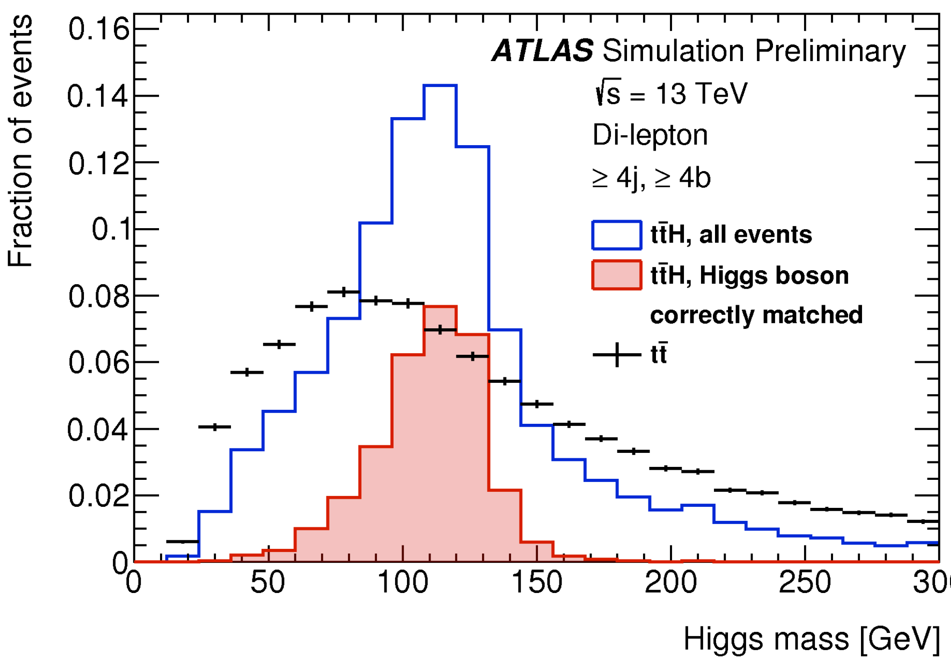


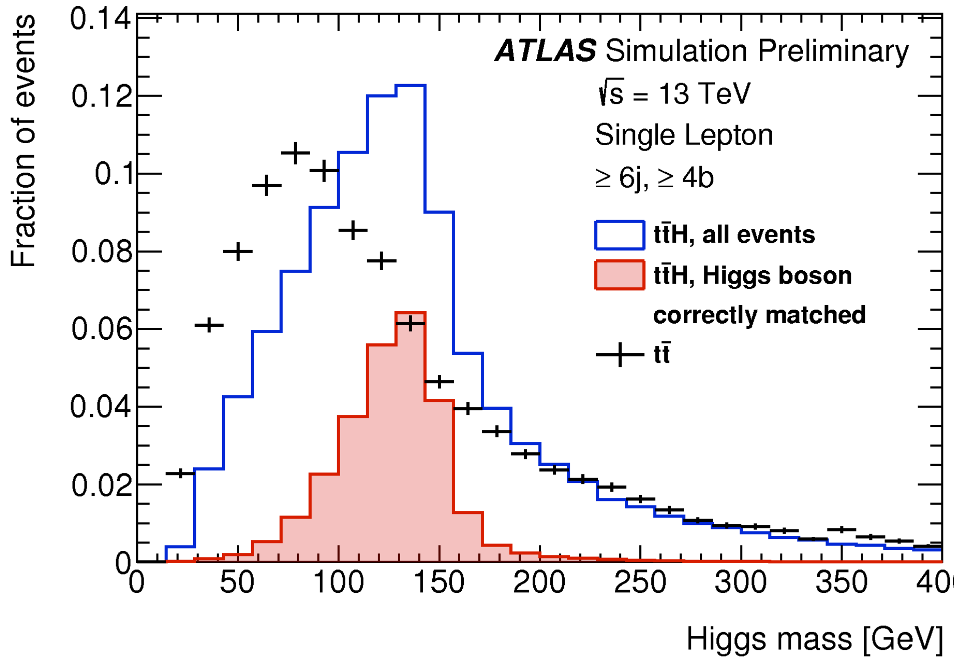


ATLAS-CONF-2016-080

m_{bb}

- Clearly, m_{bb} is a good discriminating variable
  - But resolution is poor
  - Include other variables, combine using multivariate tools (NN, BDT)



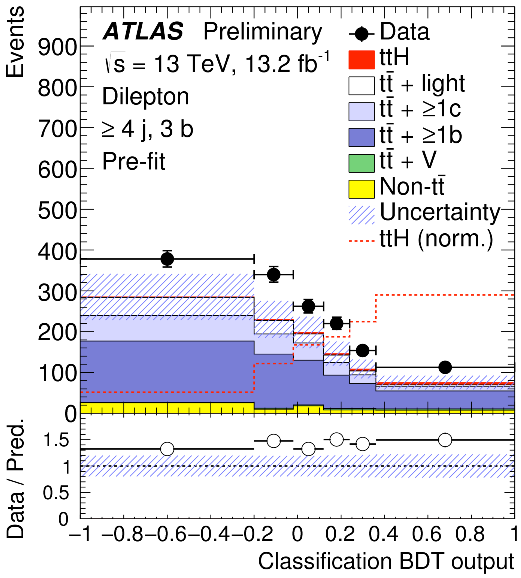


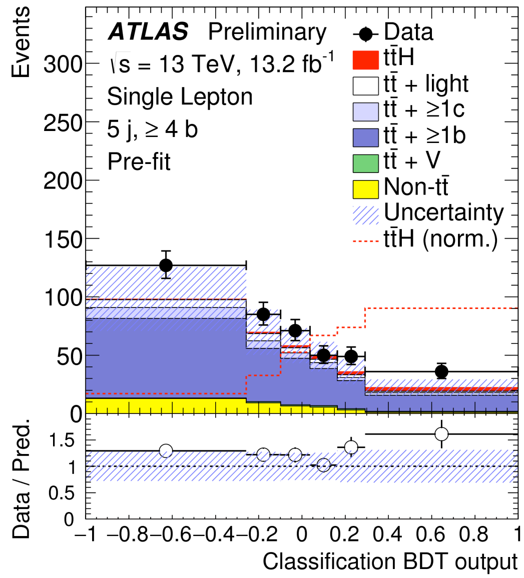
MVA

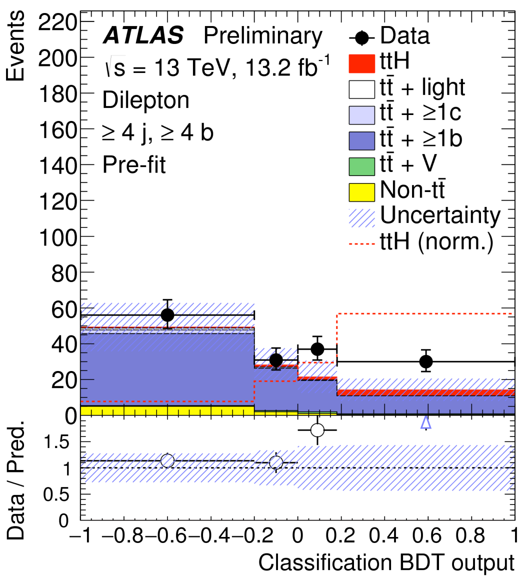
Variable	Definition	Region		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
General kinematic variables				
$\Delta\eta_{bb}^{avg}$	Average $\lvert\Delta\eta\rvert$ among pairs of b-jets	✓	–	–
$\Delta\eta_{bb}^{max}$	Maximum $\Delta\eta$ between any two b-jets	–	✓	✓
$\Delta\eta_{jj}^{avg}$	Average $\Delta\eta$ among jet pairs	–	✓	–
$\Delta R_{bb}^{max\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	✓	✓
ΔR_{bb}^{Higgs}	ΔR between the two b-tagged jets with mass closest to the Higgs boson mass	✓	–	–
$\Delta R_{bb}^{max\ m}$	ΔR between the two b-jets with the largest invariant mass	✓	✓	✓
$m_{bb}^{max\ p_T}$	Mass of the two b-tagged jets with the largest vector sum p_T	–	–	✓
m_{bb}^{Higgs}	Mass of the two b-tagged jets closest to the Higgs boson mass	✓	✓	✓
m_{bb}^{min}	Minimum mass of two b-tagged jets	–	–	✓
$m_{bb}^{min\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	✓
$p_{T,b}^{min}$	Minimum b-tagged jet p_T	–	–	✓
H_T^{all}	Scalar p_T sum of all leptons and jets	–	✓	✓
$N_{bb}^{Higgs\ 30}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$N_{jj}^{Higgs\ 30}$	Number of jet pairs with invariant mass within 30 GeV of the Higgs boson mass	–	✓	–
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Sum of the p_T divided by sum of the E for all jets and both leptons	✓	–	✓
$H2_{jets}$	Third Fox–Wolfram moment computed using all jets	–	✓	–
$H4_{all}$	Fifth Fox–Wolfram moment computed using all jets and leptons	–	–	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	–
m_H	Higgs boson mass	✓(*)	✓(*)	–
$\Delta\eta_{H,l}^{min}$	Minimum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta_{H,l}^{max}$	Maximum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta_{H,b}^{min}$	Minimum $\Delta\eta$ between the Higgs boson and a b-jet	✓*	–	–

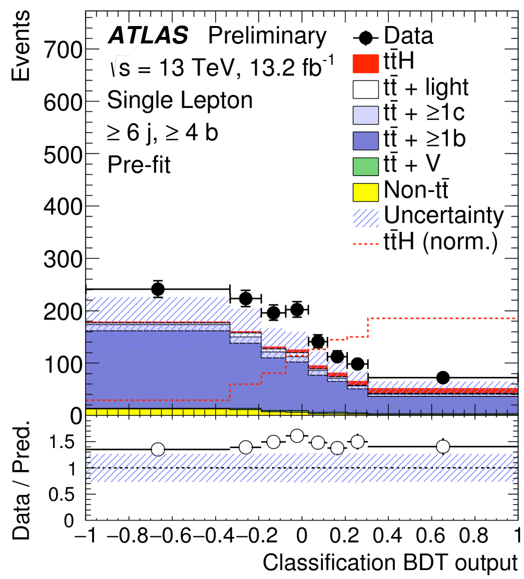
Variable	Definition	Region		
		$\geq$ 6j, $\geq$ 4b	$\geq$ 6j, 3b	5j, $\geq$ 4b
General kinematic variables				
ΔR_{bb}^{avg}	Average ΔR for all b-tagged jet pairs	✓	✓	✓
$\Delta R_{bb}^{max\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	–	–
$\Delta\eta_{jj}^{max}$	Maximum $\Delta\eta$ between any two jets	✓	✓	✓
$m_{bb}^{min\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	–
$m_{jj}^{min\ \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	–	–	✓
$m_{bj}^{max\ p_T}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_T	–	✓	–
p_T^{jet5}	p_T of the fifth leading jet	✓	✓	✓
$N_{bb}^{Higgs\ 30}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
N_{40}^{jet}	Number of jets with $p_T \geq 40GeV$	–	✓	–
H_T^{had}	Scalar sum of jet p_T	–	✓	✓
$\Delta R_{lep-bb}^{min\ \Delta R}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Scalar sum of the p_T divided by sum of the E for all jets and the lepton	✓	✓	✓
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	✓*
m_H	Higgs boson mass	✓	✓	✓
$m_{H,b_{lep\ top}}$	Mass of Higgs boson and b-jet from leptonic top	✓	–	–
$\Delta R_{Higgs\ bb}$	ΔR between b-jets from the Higgs boson	✓	✓	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs boson and $t\bar{t}$ system	✓*	✓*	✓*
$\Delta R_{H,lep\ top}$	ΔR between Higgs boson and leptonic top	✓	–	–
$\Delta R_{H,b_{had\ top}}$	ΔR between Higgs boson and b-jet from hadronic top	–	✓*	✓*

BDT Outputs

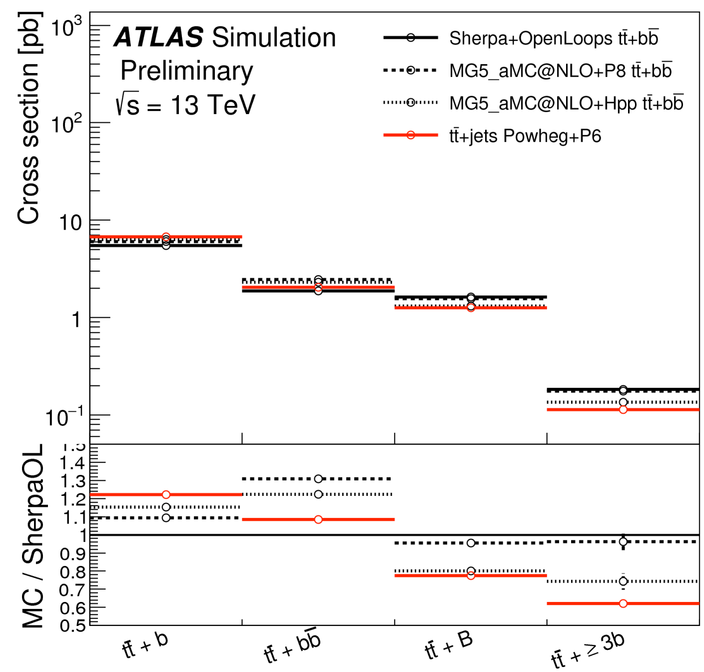






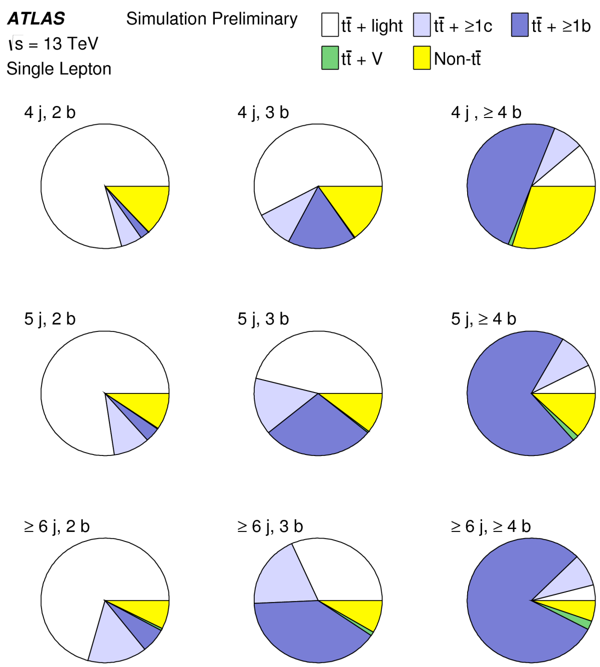


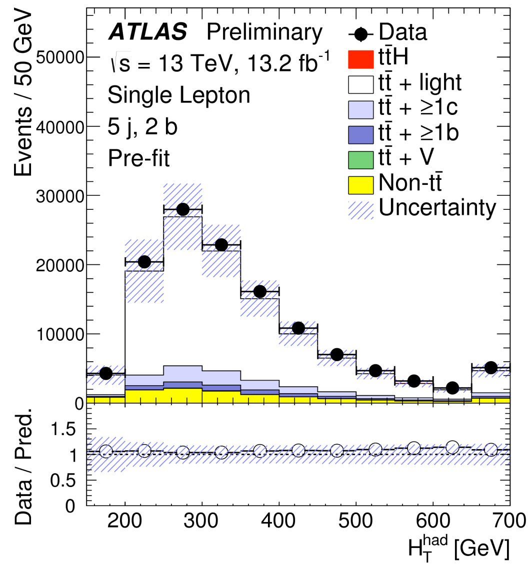
Uncertainties much larger than signal!

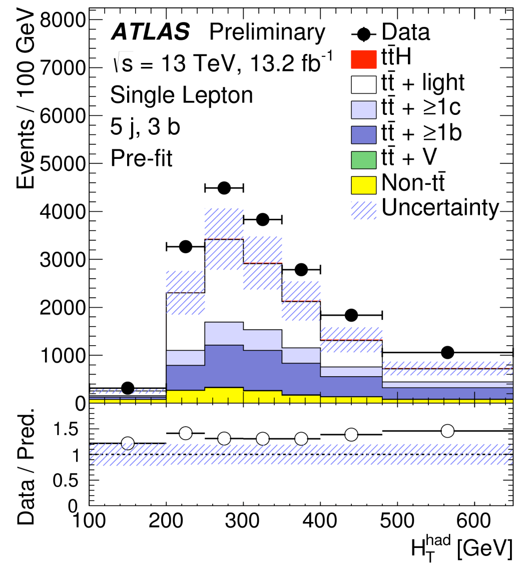


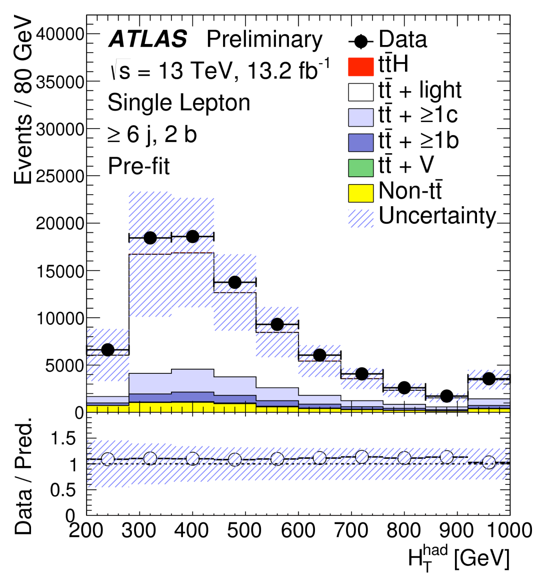
And then there are shape uncertainties

Closer Look









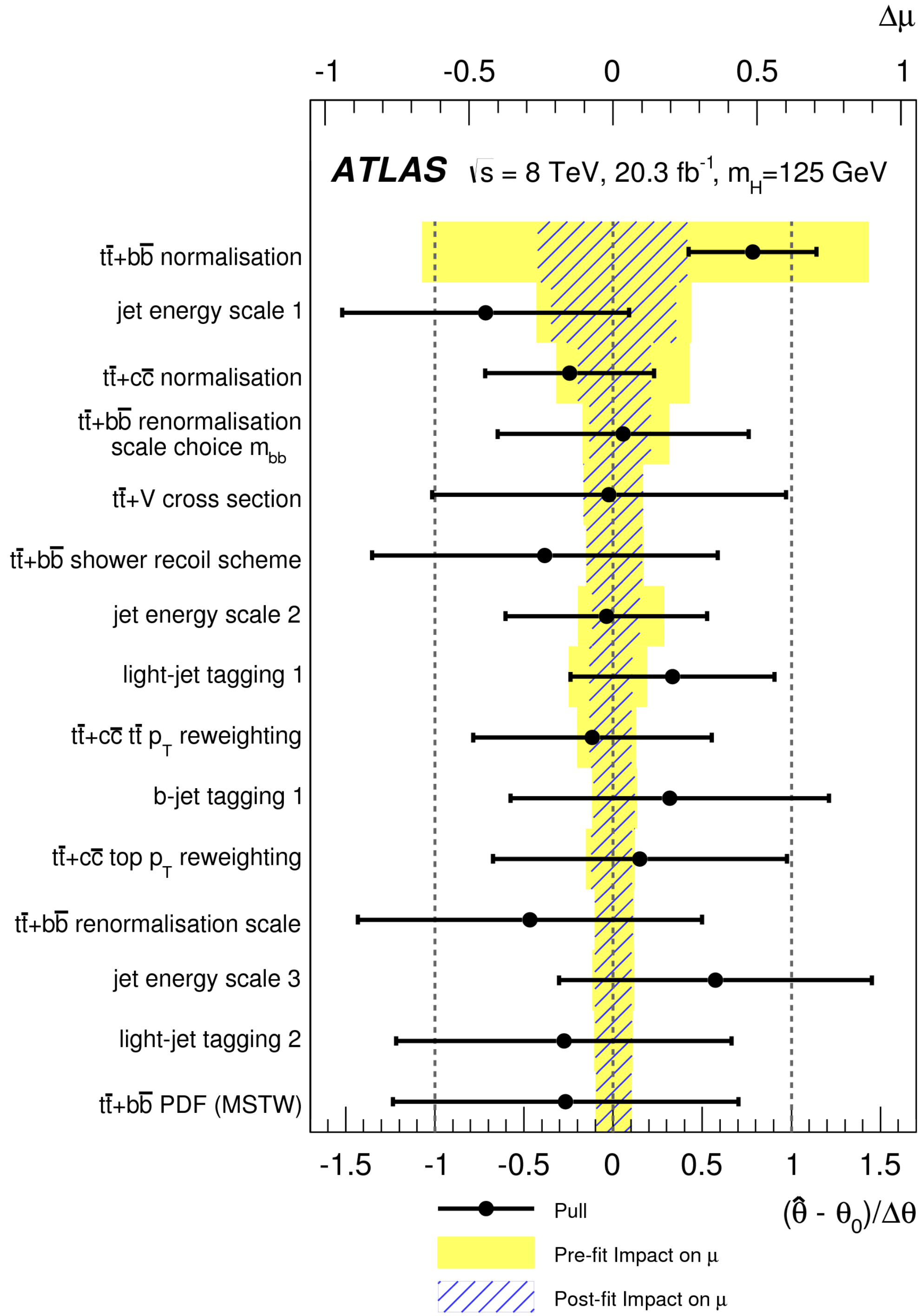
Strong handle on tt+light, ttcc and ttbb contributions

⇒

Include in fit!

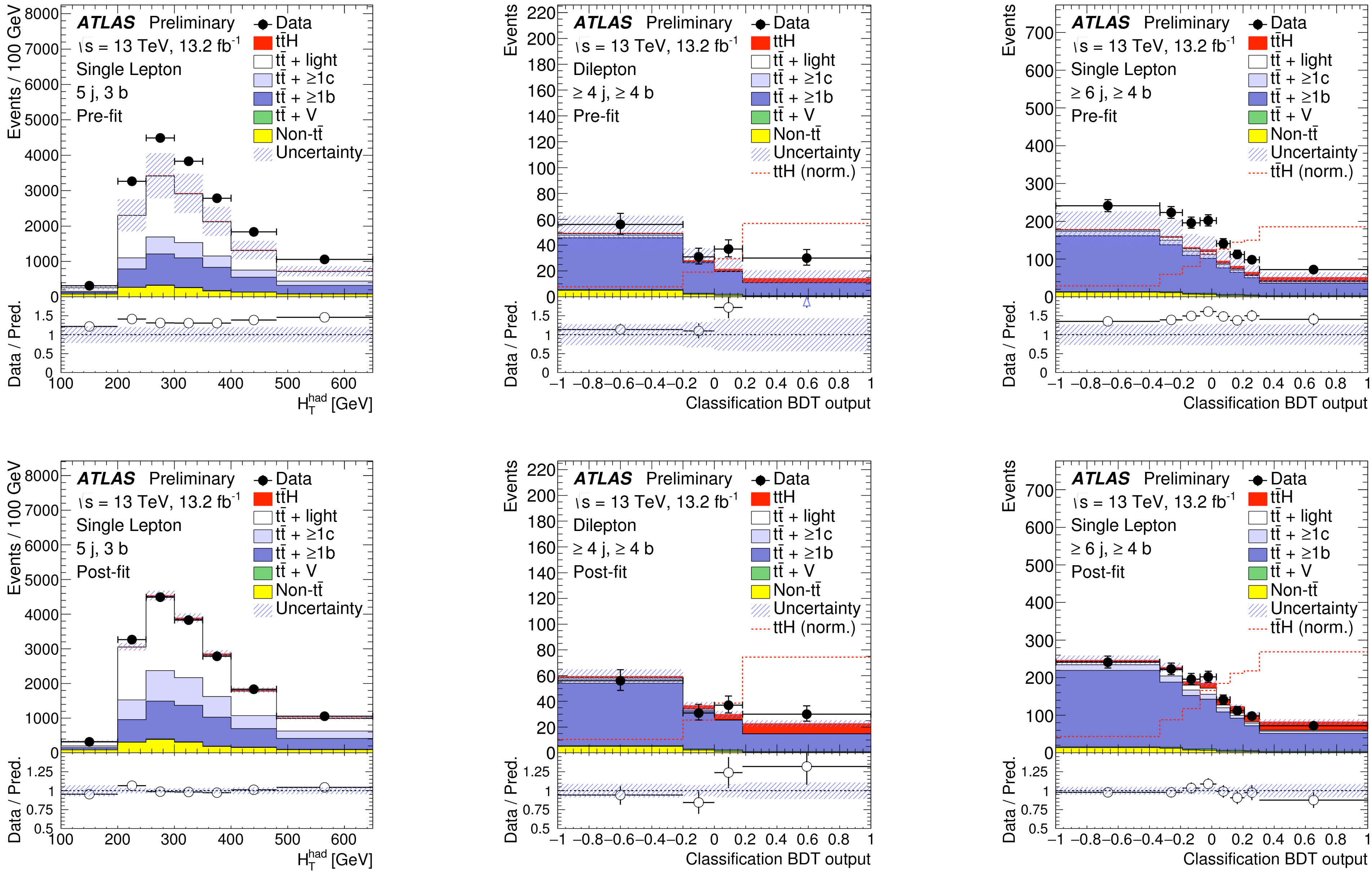
Fit Results

- Need to compare starting point and results
  - Pathologies due to lack of MC stats in some areas, strong correlations, …
- Crucial to design analysis with good control regions: fit helps address least understood systematics

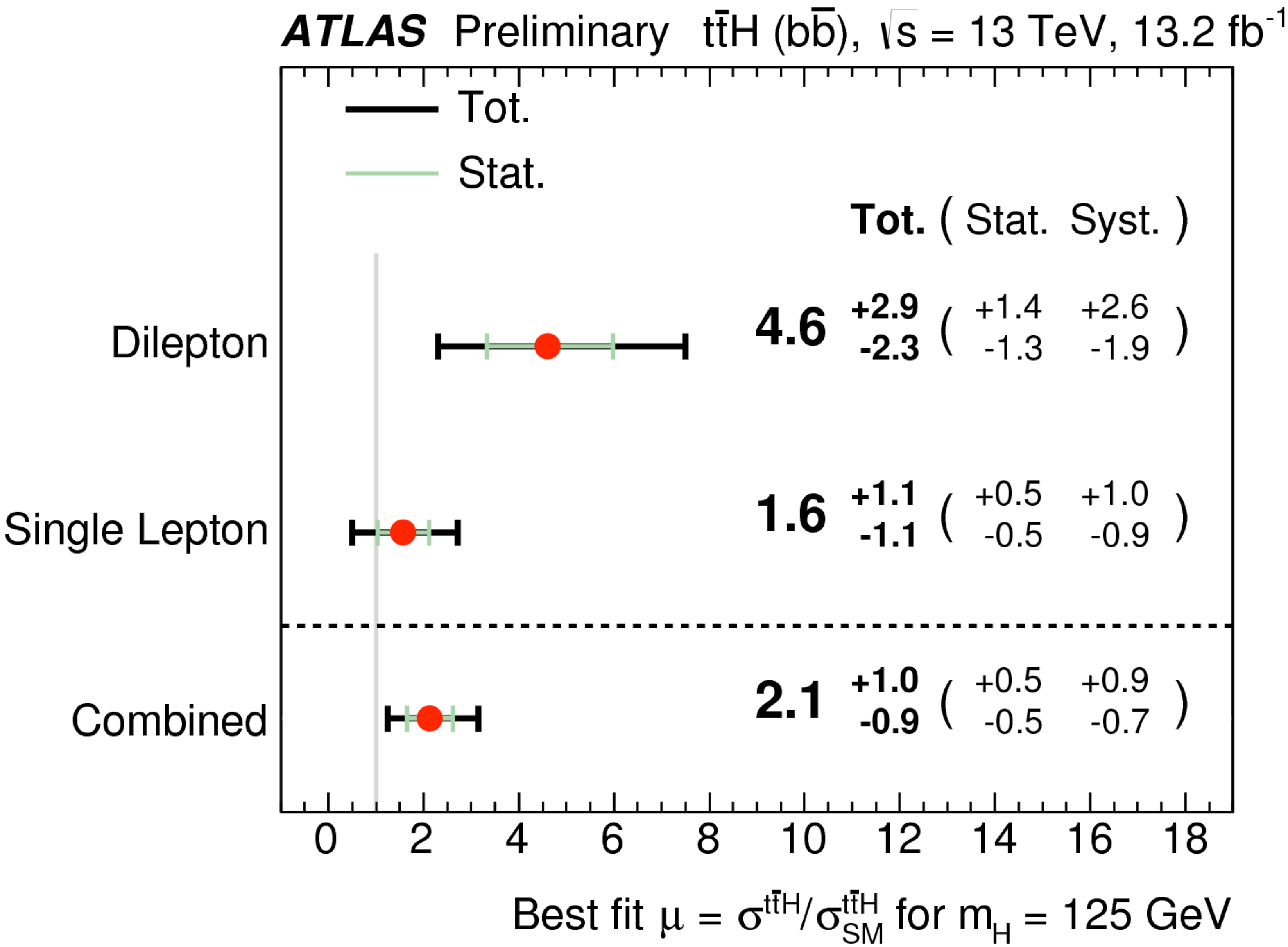


ATLAS ttH search: arXiv:1503.05066

Pre- vs Post-Fit



Oh Yeah


ATLAS Preliminary $t\bar{t}H\,(b\bar{b})$, $\sqrt{s}$ = 13 TeV, 13.2 fb^{-1}
Tot.
Stat.
Tot. (Stat. Syst.)
Dilepton
4.6 +2.9 -2.3 (+1.4 -1.3 +2.6 -1.9)
Single Lepton
1.6 +1.1 -1.1 (+0.5 -0.5 +1.0 -0.9)
Combined
2.1 +1.0 -0.9 (+0.5 -0.5 +0.9 -0.7)
0
2
4
6
8
10
12
14
16
18
Best fit $\mu = \sigma^{t\bar{t}H}/\sigma^{t\bar{t}H}_{SM}$ for m_H = 125 GeV

So, Physics Analysis

- Start from:
  - "*How well* do we understand data *and* the SM?"
    - How confident are we in corrections we apply?
- Given that:
  - Which measurements can we make? What do we need to do to improve our understanding?
- Balance the work!
  - Early, low background searches
  - Detailed understanding/verification of SM predictions

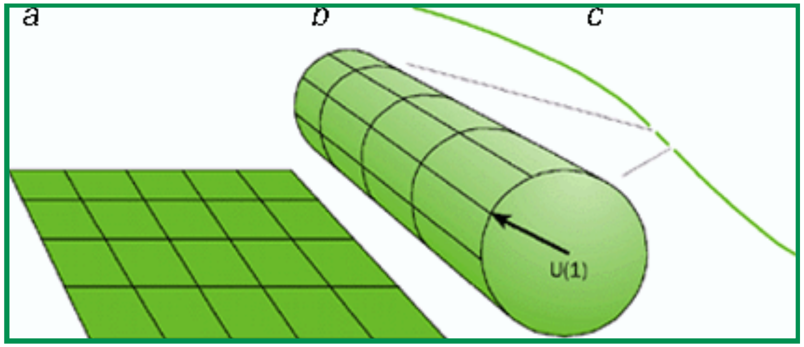
Complementary measurements!

- Increasingly complex searches
  - Tough backgrounds, hard work
  - Don't scorn multivariate and statistical tools

Excesses

Extra Dimensions

- A promising approach to quantum gravity consists in adding extra space dimensions: string theory
  - Additional space dimensions are hidden, presumably because they are compactified



Source: PhysicsWorld

- Radius of compactification usually assumed to be at the scale of gravity, i.e. 10^{18} GeV
  - In '90 Antoniadis realized they may be much larger...

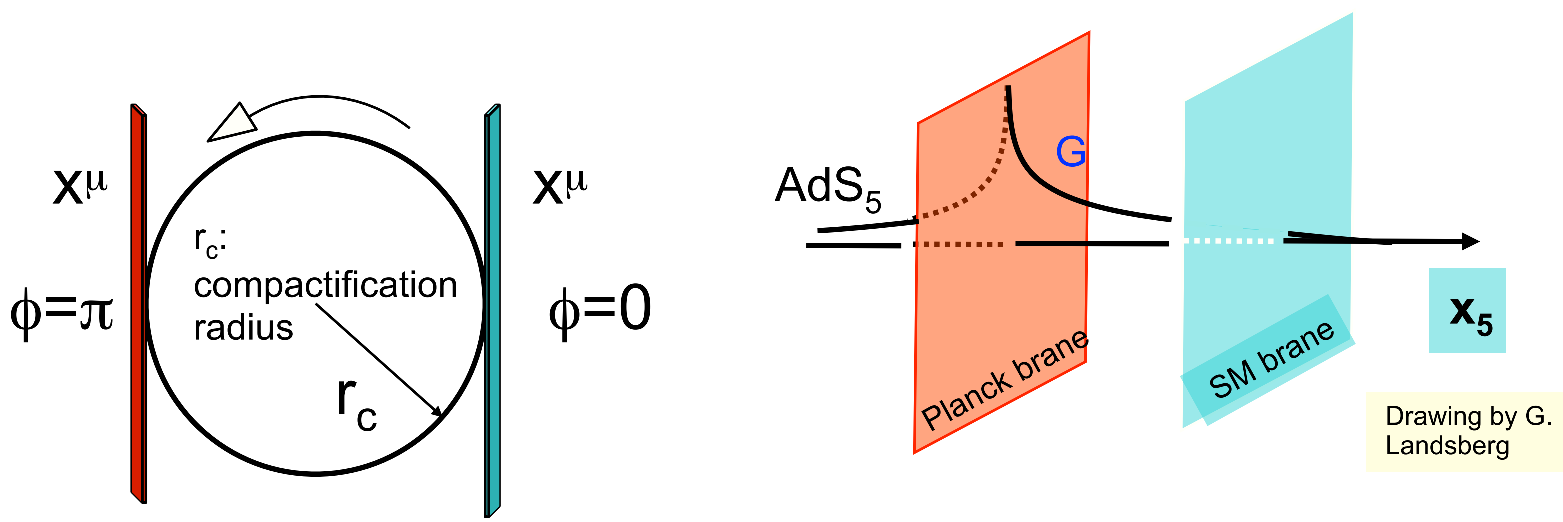
Phys.Lett.B246:377-384,1990

Warped Extra Dimensions

- "Simple" Randall-Sundrum model:

Randall & Sundrum, Phys.Rev.Lett. 83 (1999) 3370

  - SM confined to a brane, and gravity propagating in an extra dimension
  - The metric in the extra dimension is "warped" by a factor $\exp(-2kr_c\phi)$
  - (Requires 2 branes)

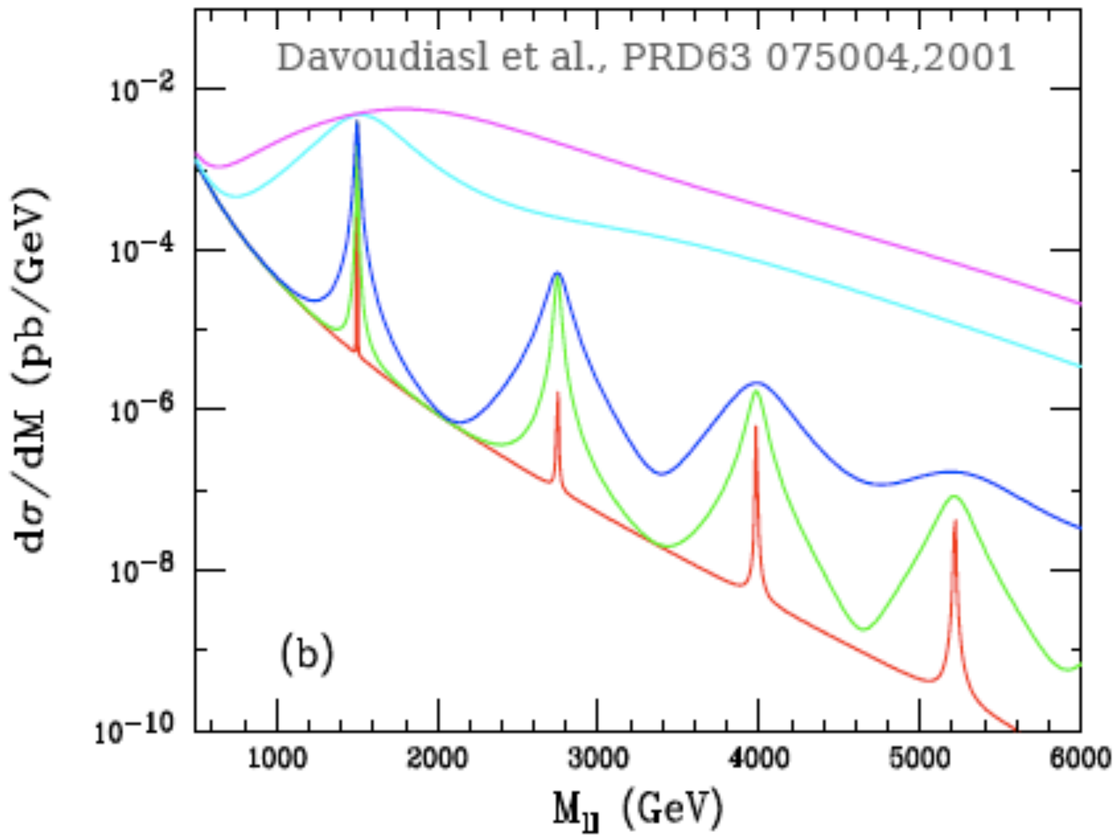


Graviton Excitations

- In RS, get a few massive graviton excitations
  - Widths depend on warp factor k
  - Mass separation = zeros of Bessel function

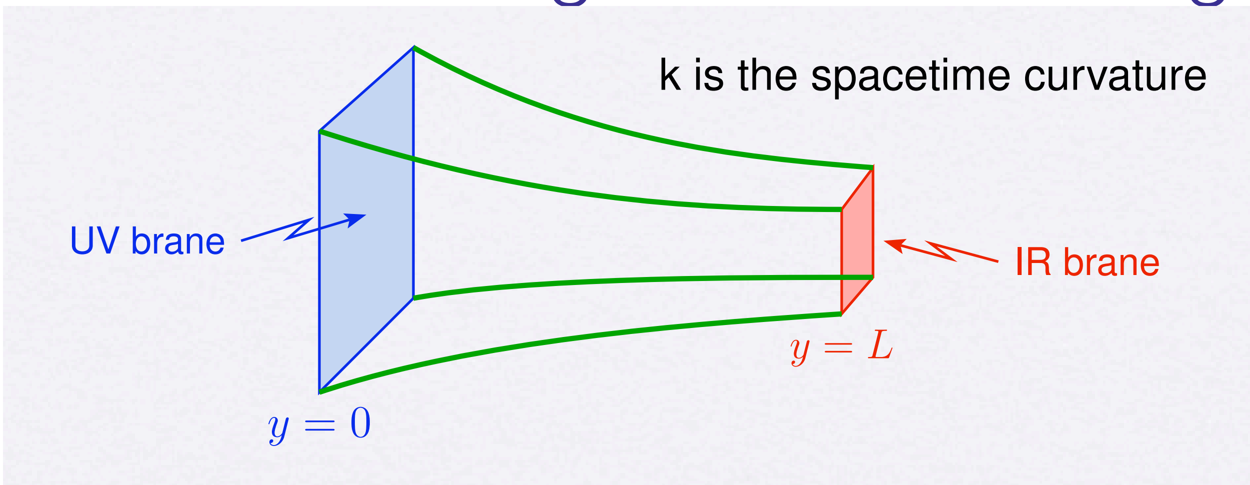
➡ Smoking gun!

(BRs also different than Z':
e.g. γγ allowed)



Hierarchies

- Physics on a curved gravitational background:

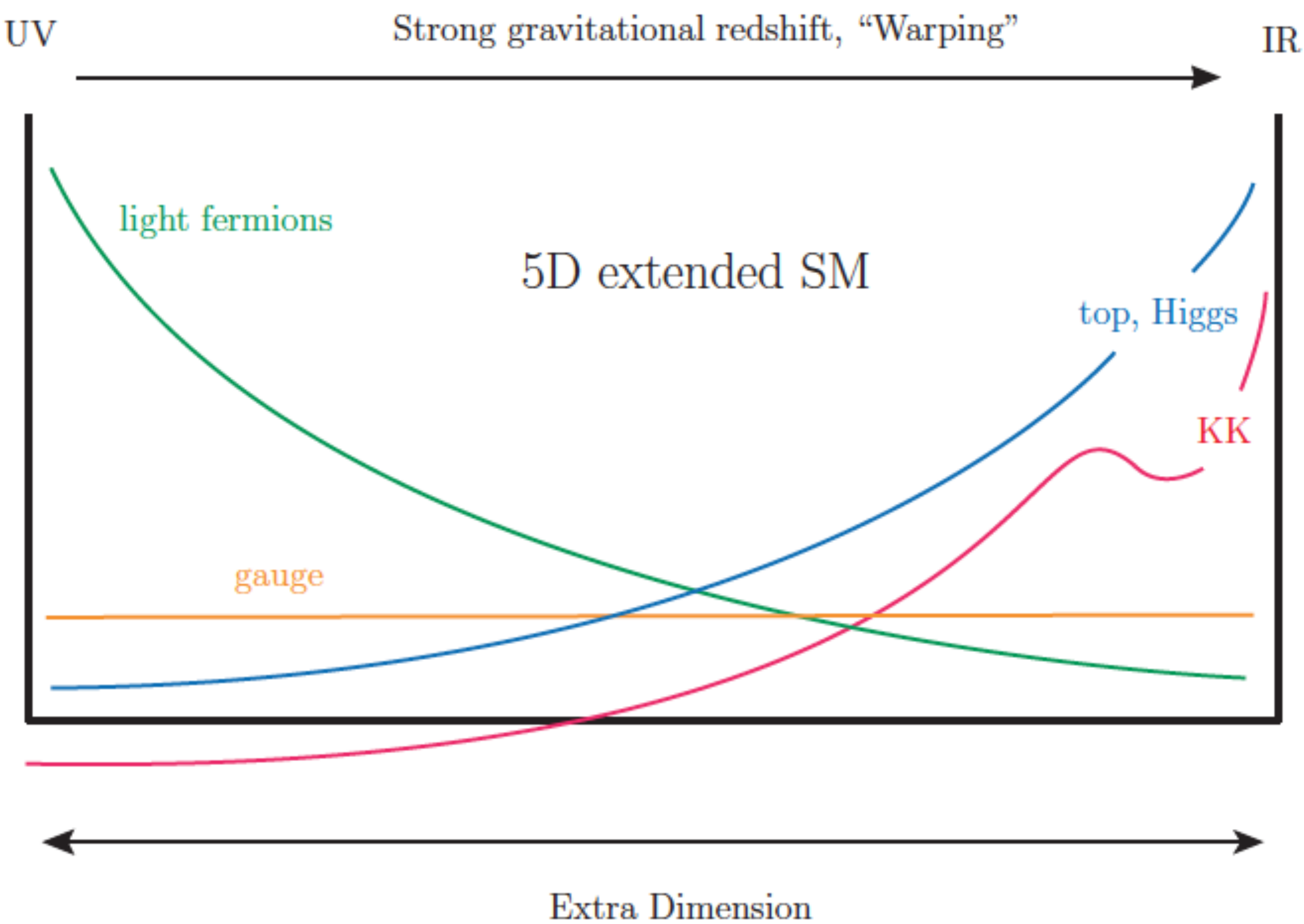


- Scales depend on position along extra dimensions
  - UV brane scale is $M_{Pl} = 2 \times 10^{18}$ GeV
  - IR brane scale is $M_{Pl}\, e^{-kL} \sim 1$ TeV if $kL \sim 30$
- If were to localize Higgs on IR brane, naturally get EW scale ~ 1TeV (from geometry!)

Flavor

- Interesting variation has fermions located along the extra dimension
  - Fermion masses generated by geometry
  - Heavier fermions are closer to IR brane, and gauge boson excitations as well
    - Gauge boson excitations expected to have masses in the 3-4 TeV range (bounds from precision measurements)
    - Couple mainly to top/W/Z (!)
  - Flavor changing determined by overlap of fermion "wave function" in the ED
    - Nice suppression of FCNC etc.

Graphically

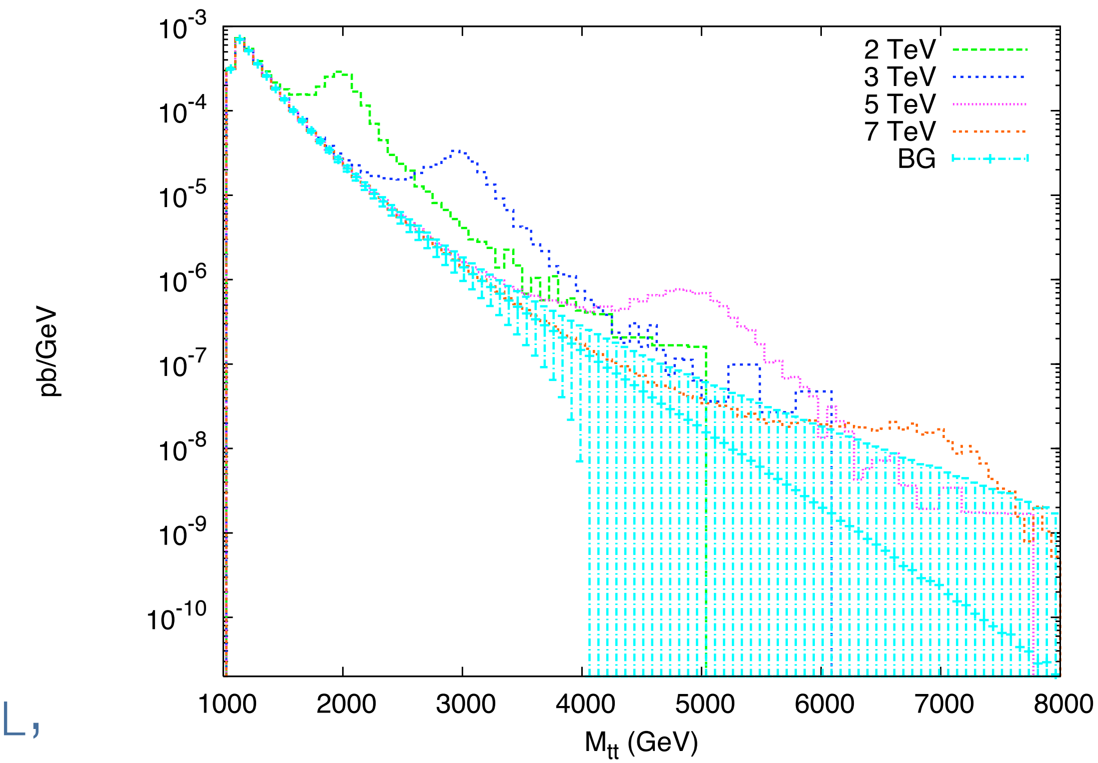


(From K Agashe et al, arXiv:1608.00526)

Gauge Boson Excitations

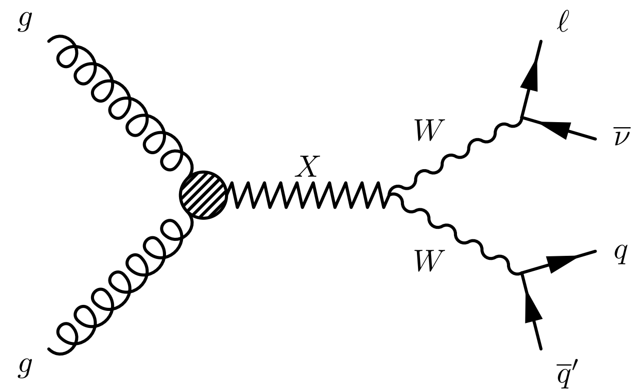
- Excitations of the gauge bosons are very promising channels for discovery
  - Couplings to light fermions are small
    - Small production cross-sections
  - Large coupling to top, W_L, Z_L
    - Look for $t\bar{t}$, WW, ZZ resonances (that can be wide)

B. Lillie et al., JHEP 0709:074,2007

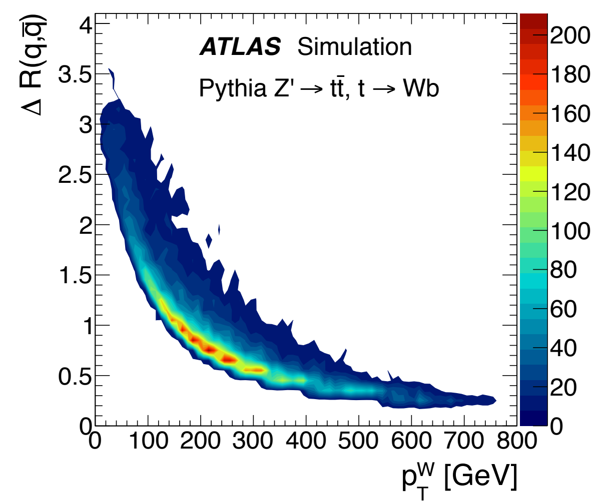


Dibosons

- ❖ Signature of Randall-Sundrum excitations as well as W', Z'
  - Can look for e.g. W' → WZ, WH
    - Many final state options: lνll, lνqq, qqll, qqqq, …
    - Three leptons → low background but low branching ratio: good at low mass where backgrounds are large
    - Fully hadronic → high branching ratio but substantial multi-jet background: good at high mass where cross-section is lower



- ❖ For high mass W', Z' decay products are boosted…ok for leptonic decays,
  - … but hadronic decay products merge:
    - $\Delta R \sim 2m/p_T \Rightarrow$ for $p_T \sim 500$ GeV, $\Delta R \sim 0.4$, typical jet size

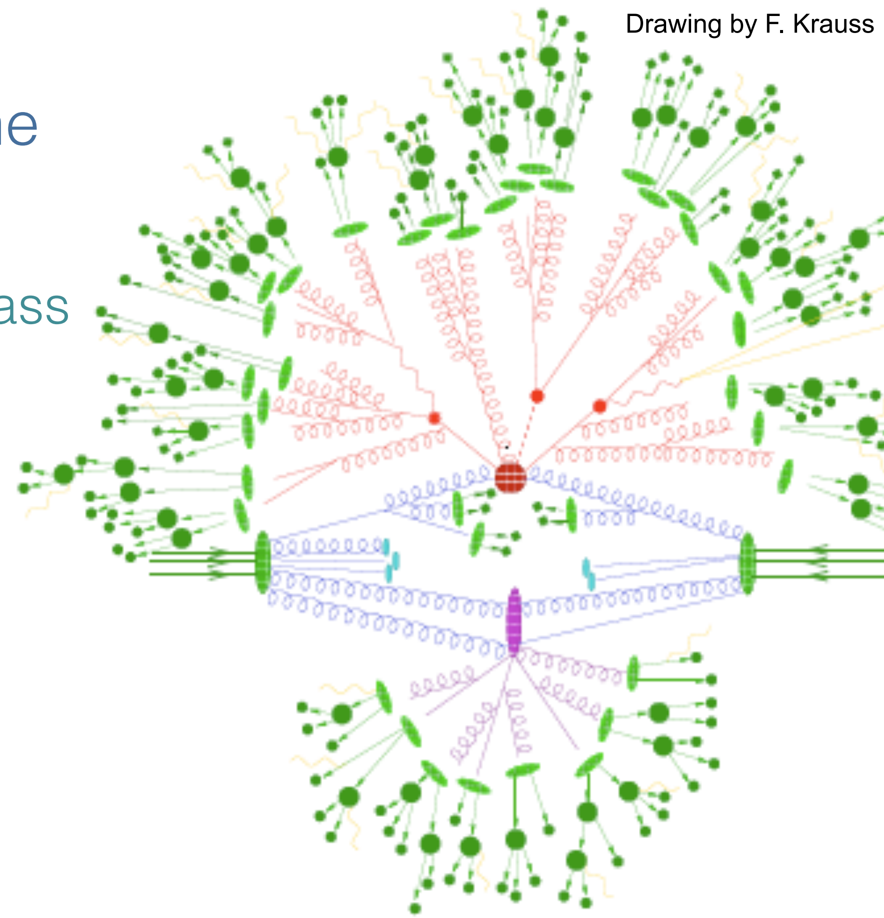


Fully Hadronic Decays

- Decay hadrons reconstructed as a single jet
  - But even if it looks like a single jet, it originates from a massive particle decaying to two (W, Z, H) or three (top) hard partons, not one
  - If I measured each of the partons in the jet perfectly, I would be able to:
    - Reconstruct the "originator's" invariant mass
    - Reconstruct the direct daughter partons

But

- Quarks hadronize → cross-talk
- My detector can't resolve all individual hadrons



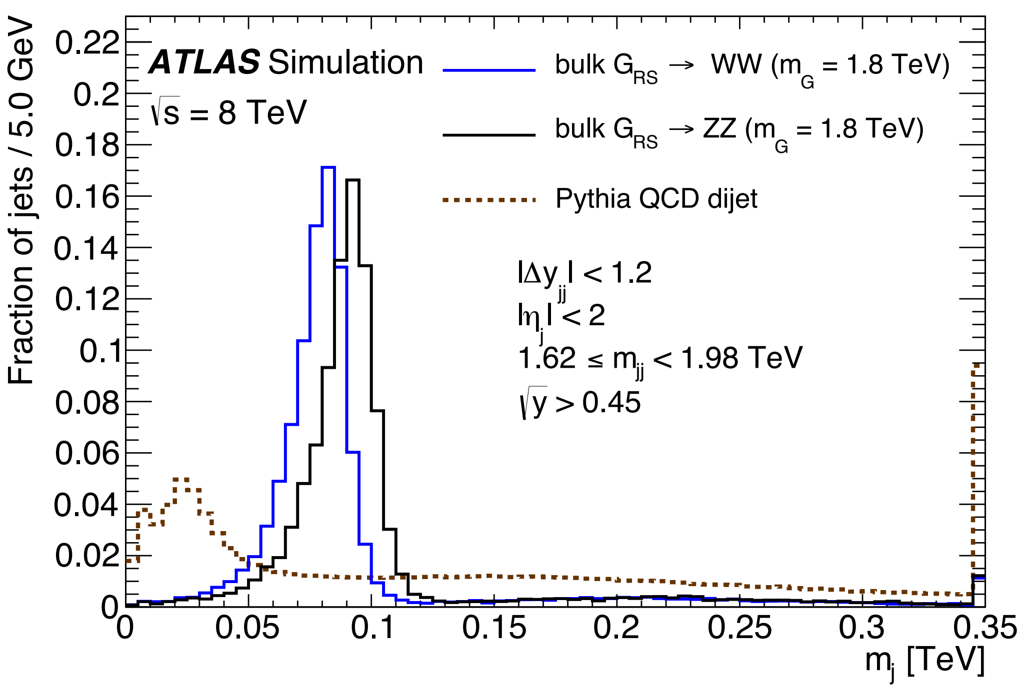
Drawing by F. Krauss

Jet Mass

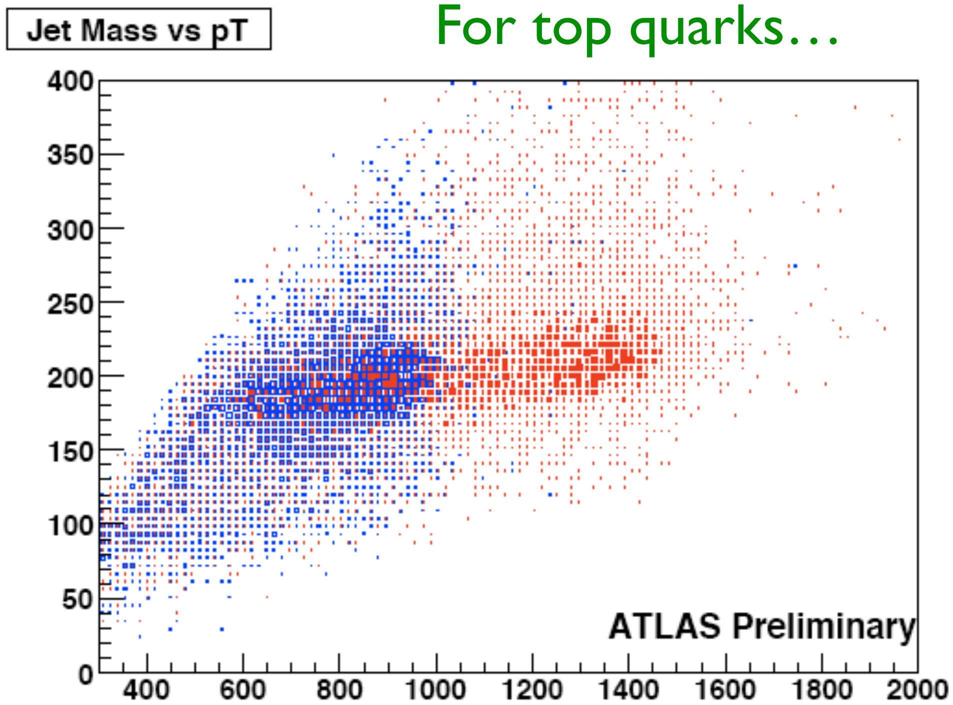
❖ Jet mass: invariant mass of all jet constituents

- In principle, close to object mass
- and invariant!

ATLAS, arXiv:1506.00962

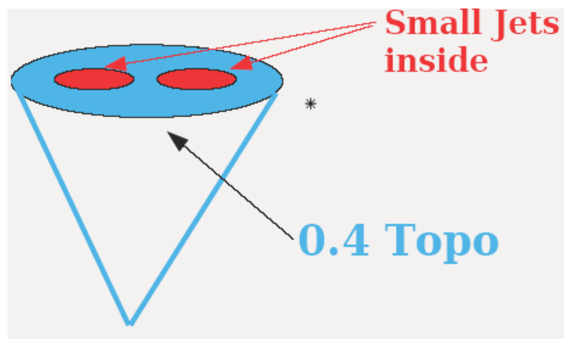


For top quarks…



Subjets

- Jet mass is not sensitive to structure
  - Can't tell whether a jet is isotropic or not
- Expect "blobs" with higher concentration of energy for jets from top/W/Z decays



- Multiple ways of exploiting this....
  - k_T splitting scales, "mass drop", …

J. M. Butterworth, B. E. Cox, and J. R. Forshaw, *Phys. Rev.* **D65** (2002) 096014

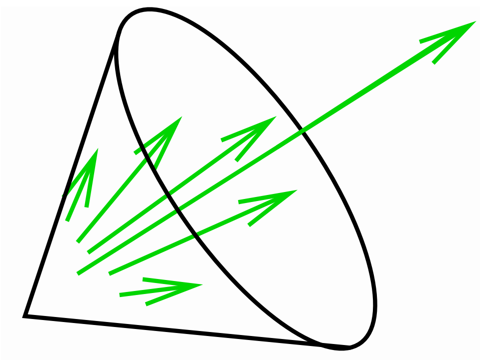
k_T Splitting Scales

- k_T jet algorithm is much better suited to understand jet substructure than cone:
  - Cone maximizes energy in an η x ϕ cone
  - k_T is a "nearest neighbor" clusterer

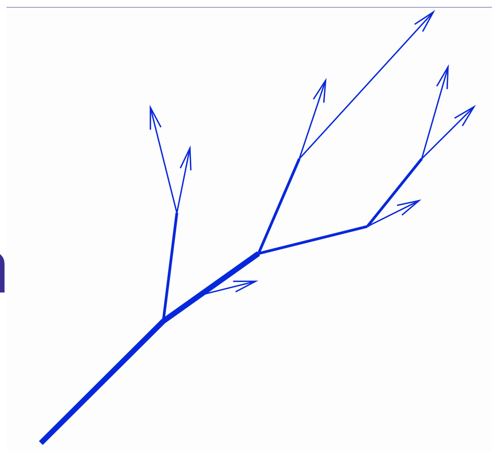
$$y_2 = \min\left(E_a^2, E_b^2\right) \bullet \theta_{ab}^2 / p_{T(jet)}^2$$

$$Y \text{ scale} = \sqrt{p_{T(jet)}^2 \bullet y_2}$$

- Can use the k_T algorithm on jet constituents and get the (y-)scale at which one switches from 1 → 2 (→ 3 etc.) jets
  - Scale is related to mass of the decaying particle

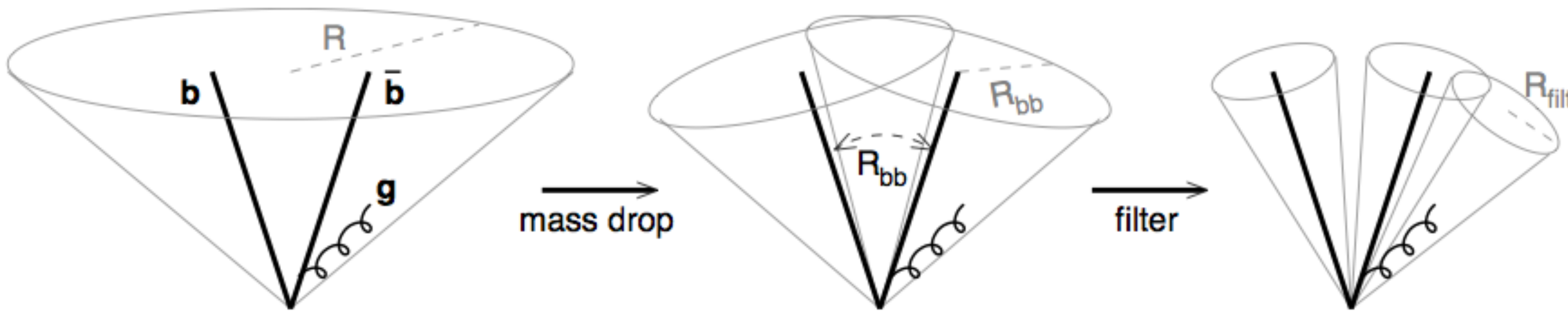


Cone



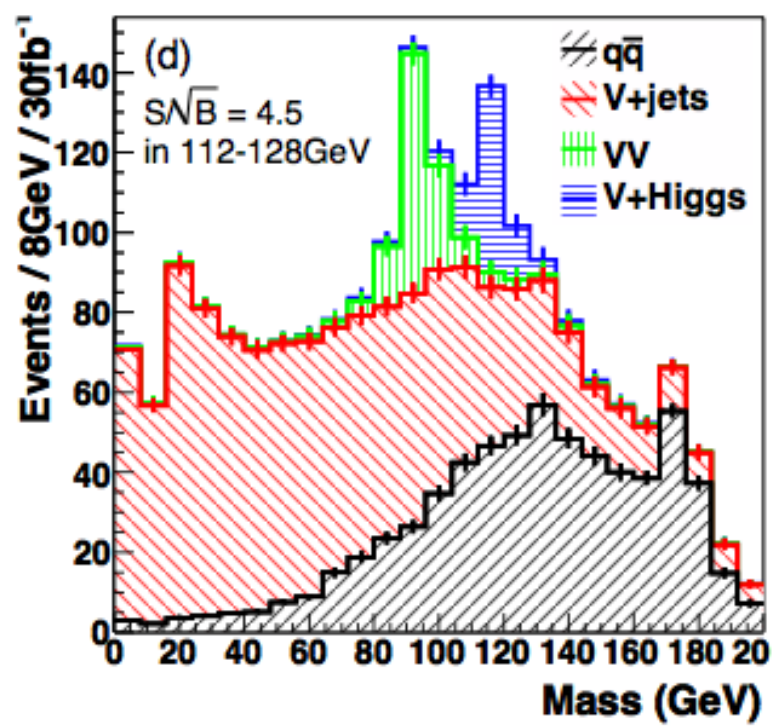
k_T

Mass Drop



BDRS, Phys.Rev.Lett. 100 (2008) 242001

- ❖ Introduced to recover (W/Z)H→ (W/Z)bb at the LHC
  - In boosted regime, Wbb and Zbb backgrounds easier to manage
  - But strategy can be used more generically

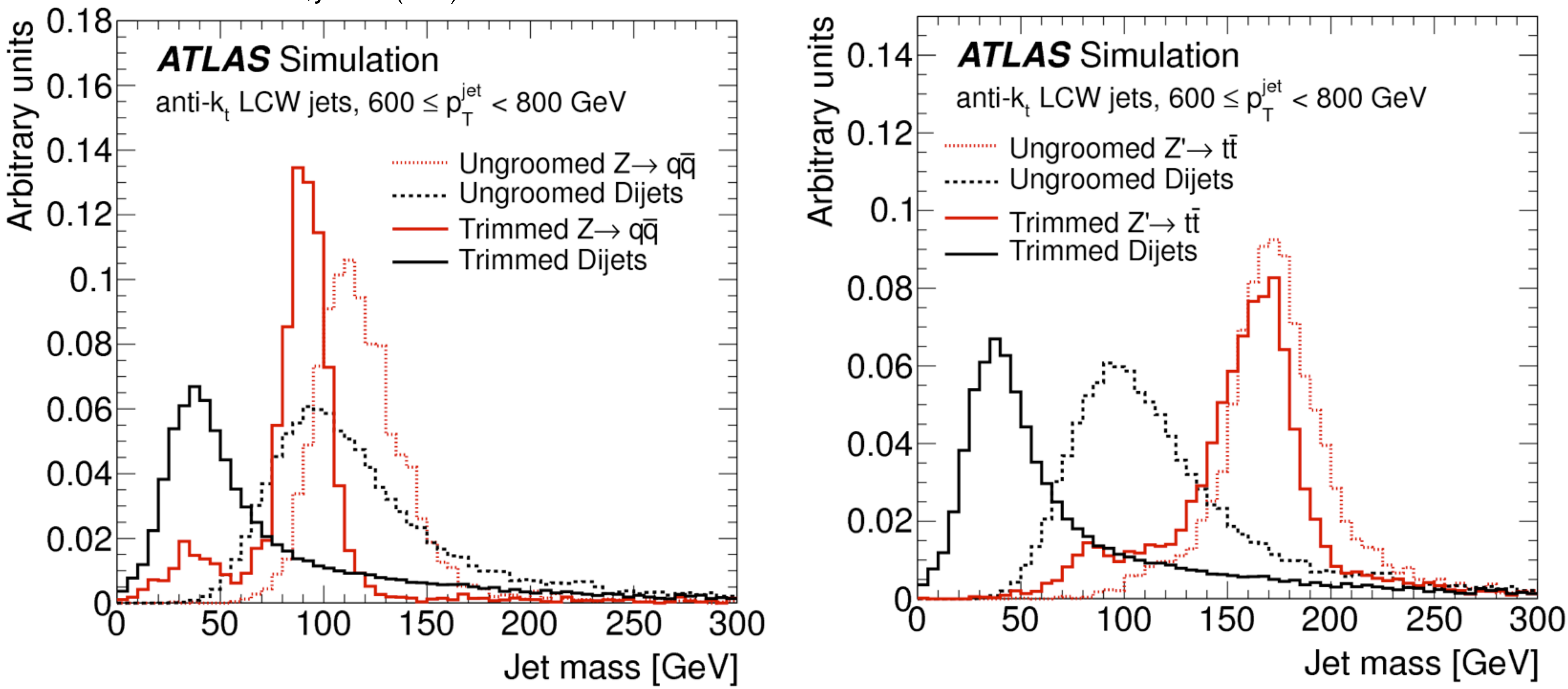


Grooming

❖ Decluster (or recluster with small R), and remove soft stuff

- Clean up soft QCD radiation/connection to underlying event

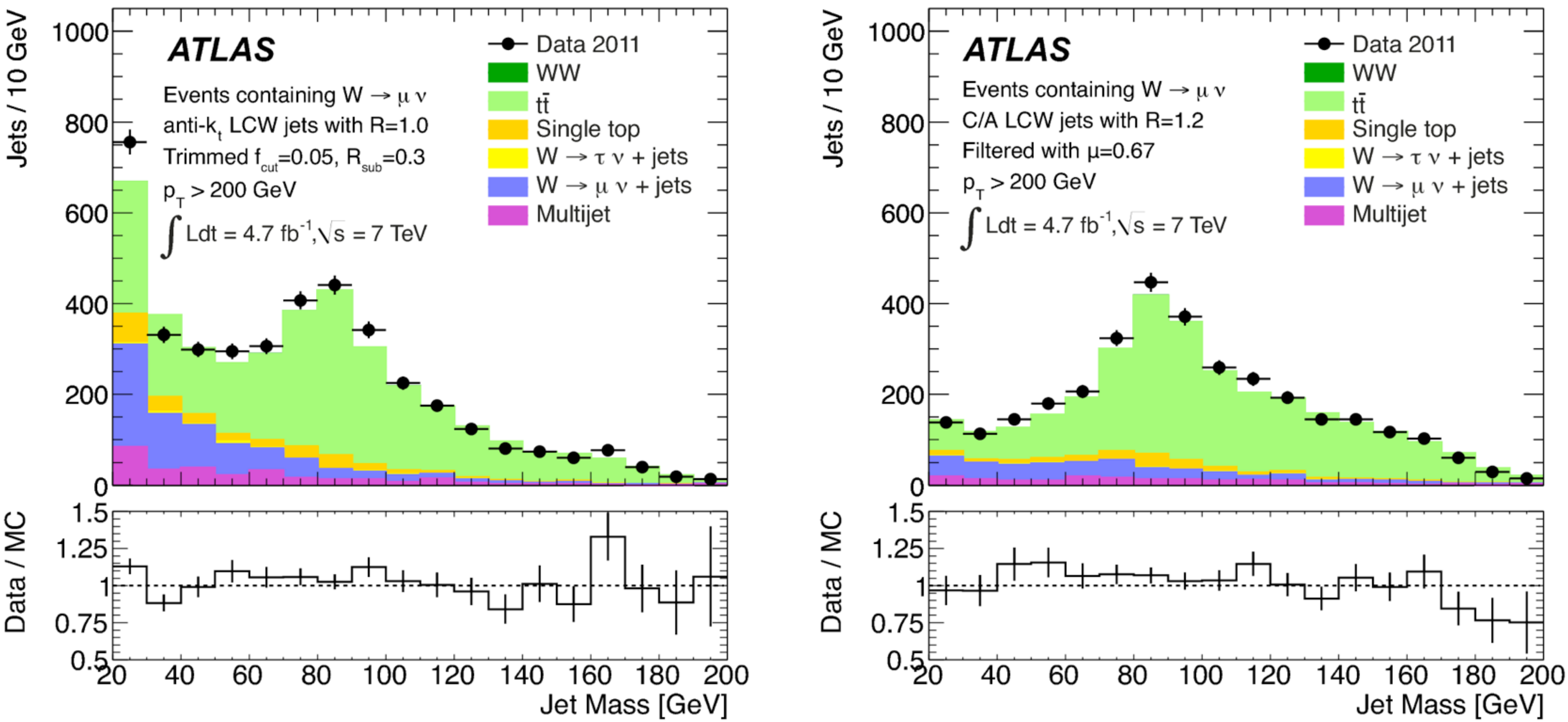
ATLAS, JHEP09 (2013) 076



Proof of Principle

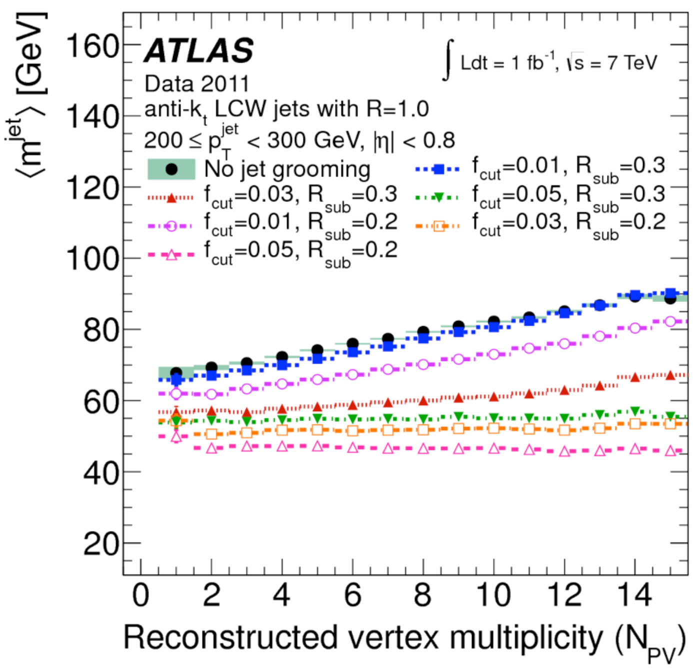
- W-jets from top quarks

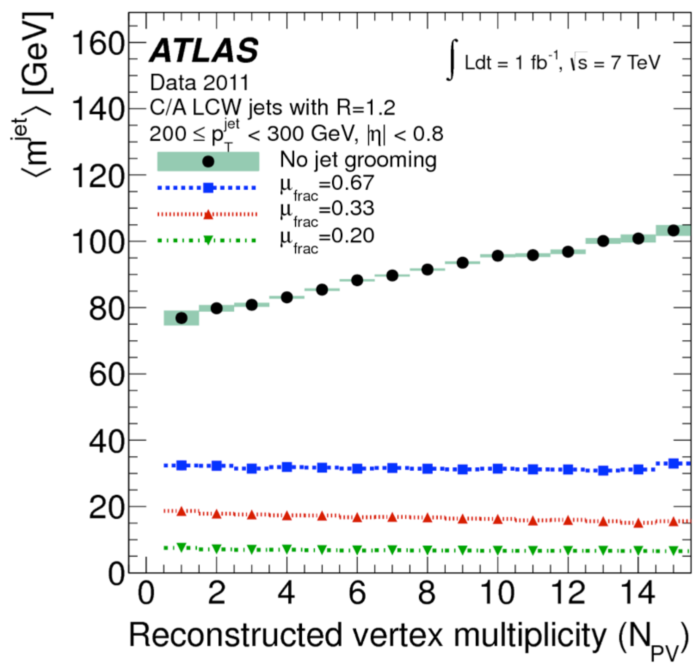
ATLAS, JHEP09 (2013) 076



Added Benefits

- ❖ Pile-up is a big deal at hadron colliders
  - Low-p_T, “uninteresting” QCD will always have a much larger cross-section than rare processes we’re hunting





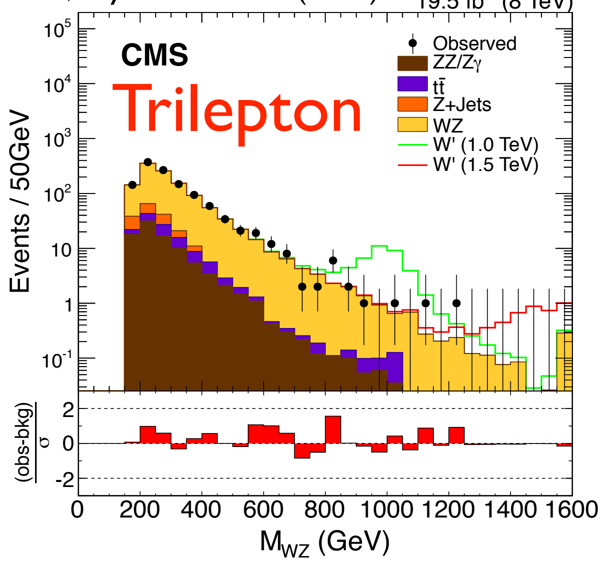
!Optimal parameter set/strategy is detector-dependent!

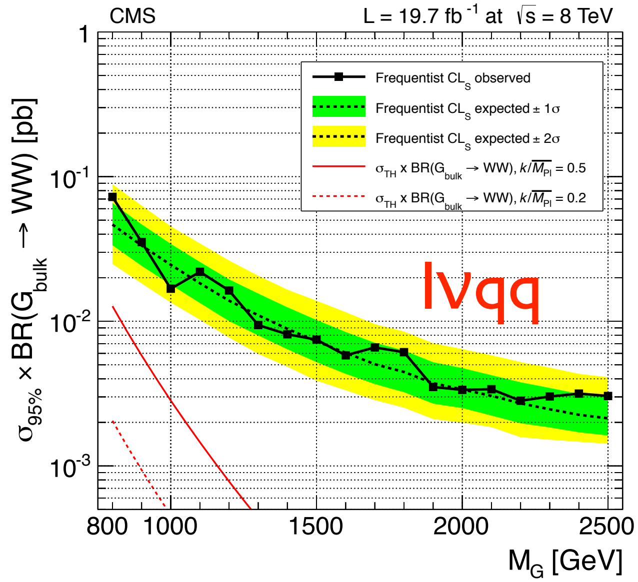
Many More Techniques

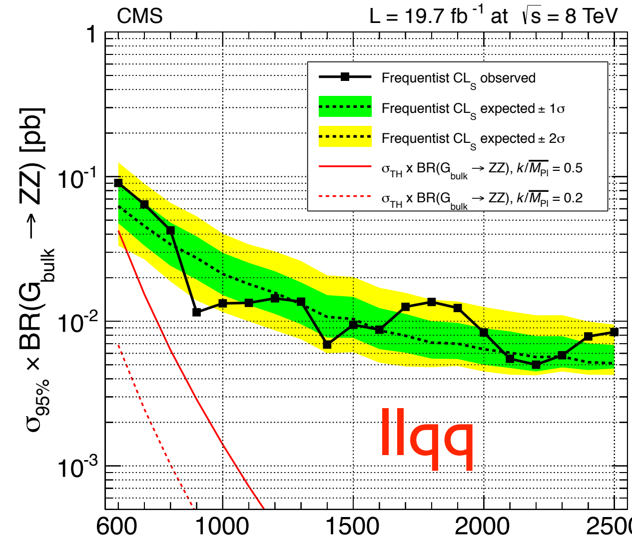
- Whole "jet structure" community exists
  - Reports of BOOST workshops a very useful resource:
    - **Boosted objects: A Probe of beyond the Standard Model physics, A. Abdesselam et al, Eur.Phys.J. C71 (2011) 1661; Jet Substructure at the Tevatron and LHC: New results, new tools, new benchmarks, A. Abdesselam et al, J.Phys. G39 (2012) 063001**
  - Direct comparison of multiple taggers, and "groomers"
  - More tools have been developed, and also more extensive non-perturbative calculations of the jet structure
  - Many of the tools available in the fastjet library (Cacciari, Salam, Soyez)
    - http://www.lpthe.jussieu.fr/~salam/fastjet/

Diboson Resonance Results: CMS

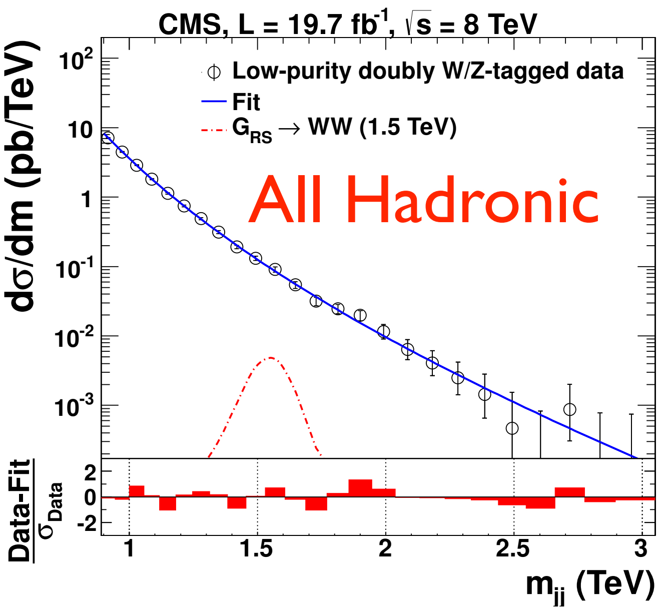
CMS, Phys. Lett. B 740 (2015) 83

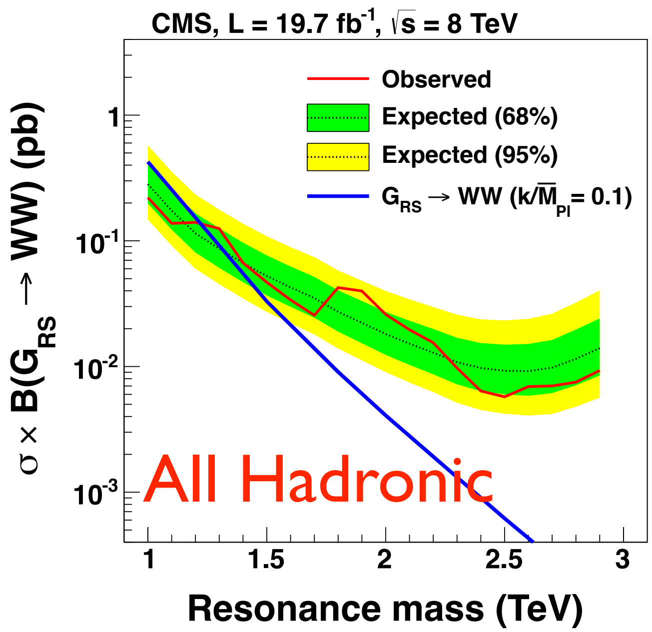






CMS, J. High Energy Phys. 08 (2014) 174



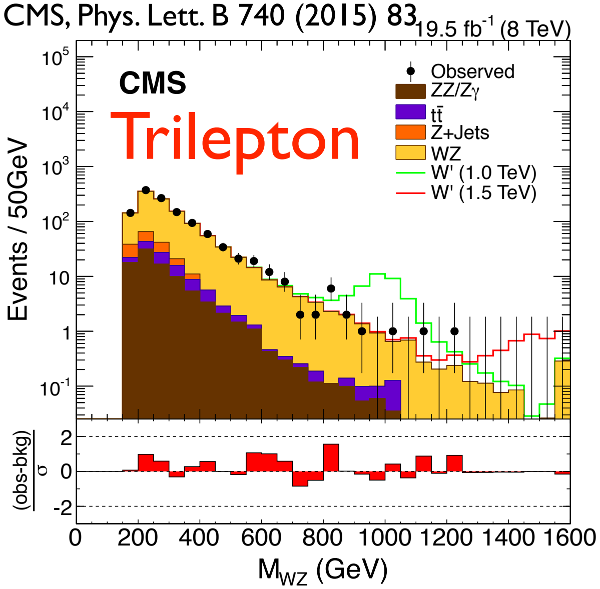


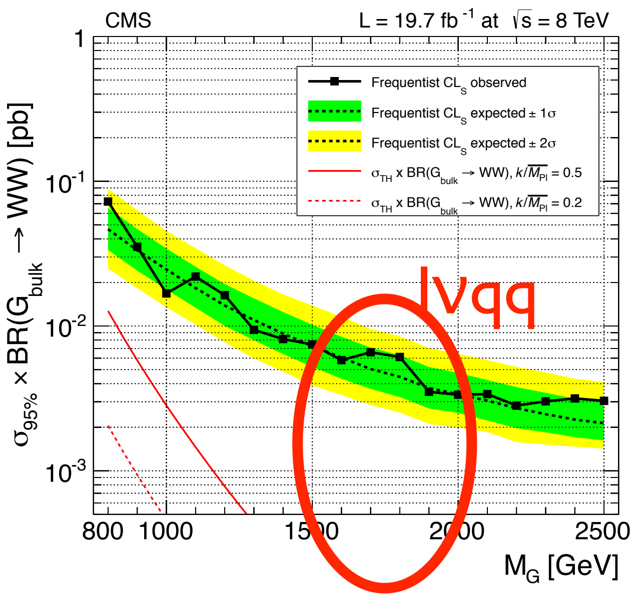
CMS, J. High Energy Phys. 08 (2014) 173

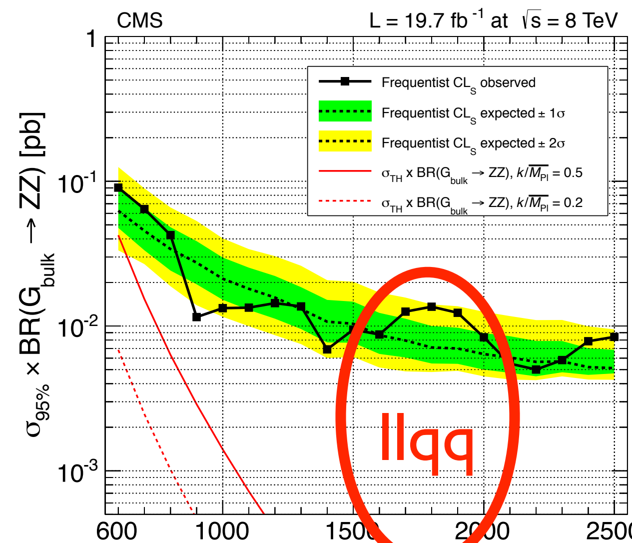
No evidence…

Diboson Resonance Results: CMS

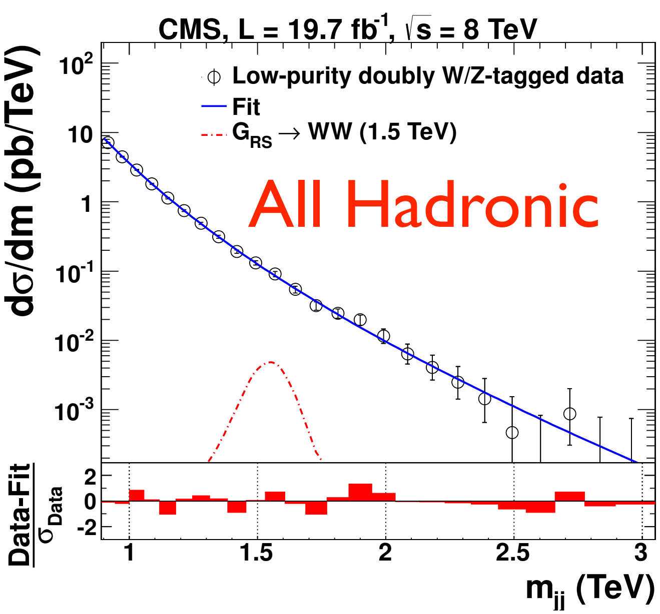
CMS, Phys. Lett. B 740 (2015) 83

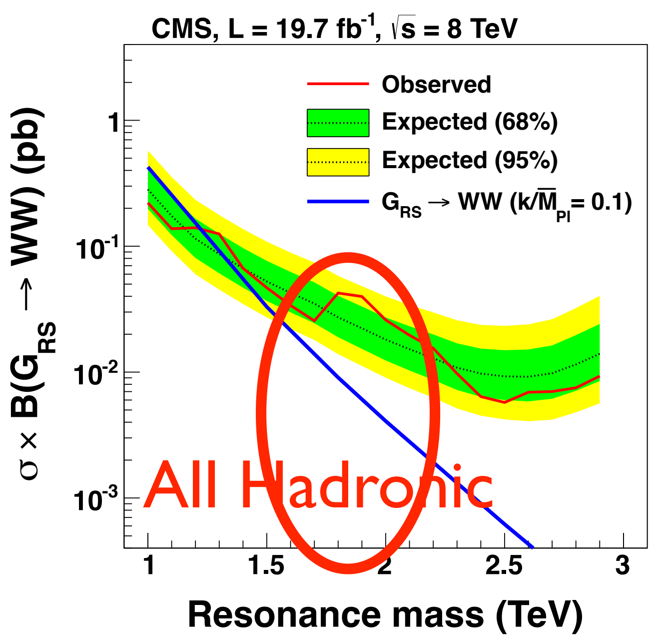






CMS, J. High Energy Phys. 08 (2014) 174





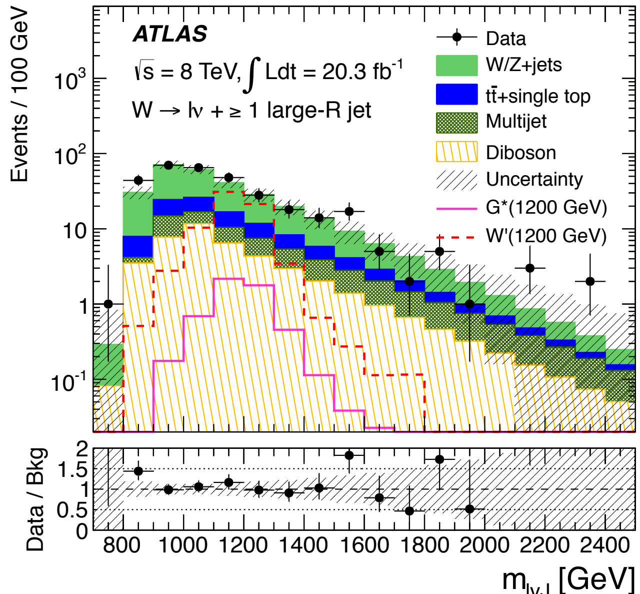
CMS, J. High Energy Phys. 08 (2014) 173

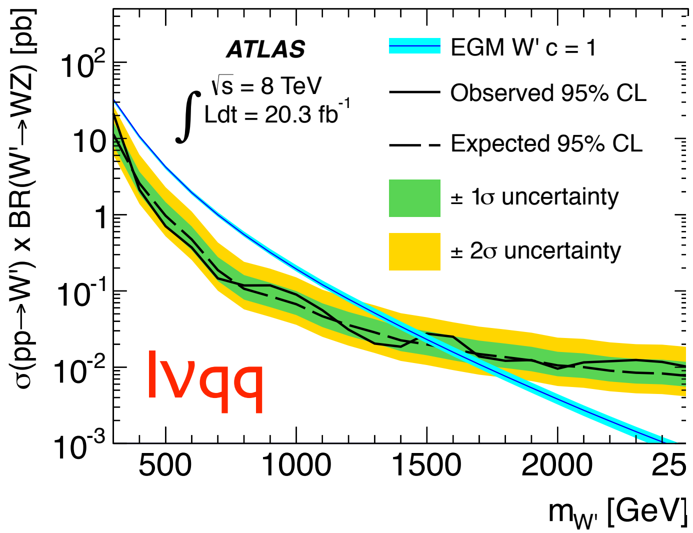
No evidence…

but a coincidence?

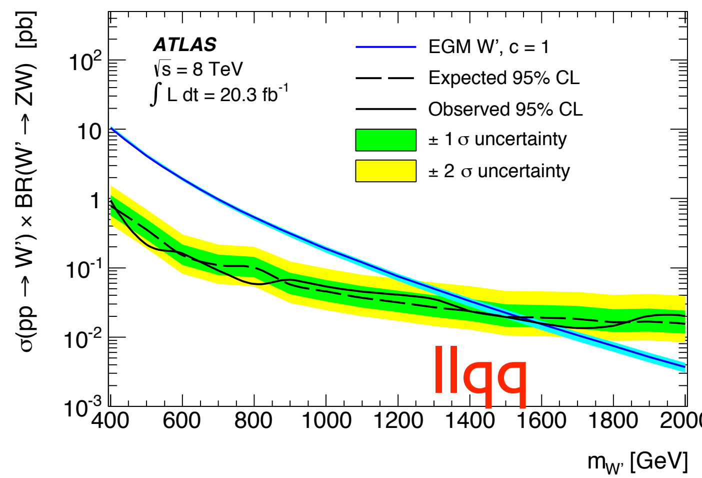
Diboson Resonance Results: ATLAS

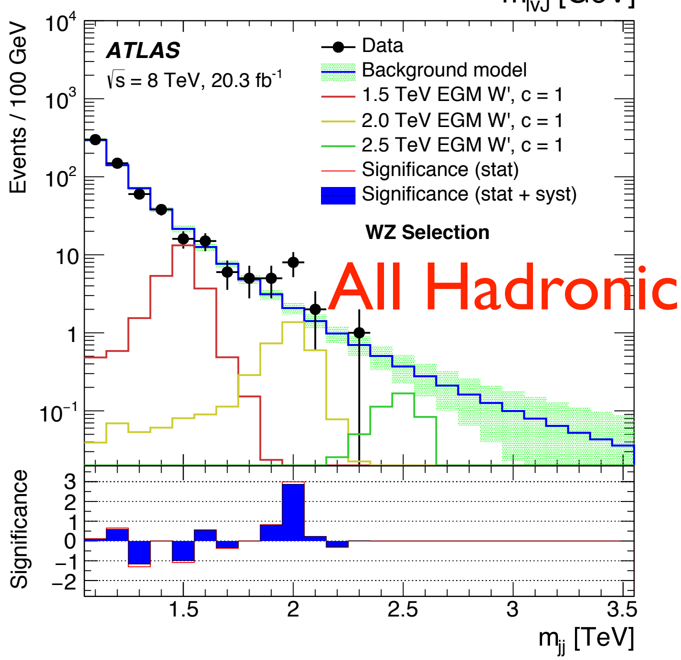
ATLAS, Eur. Phys. J. C (2015) 75:209



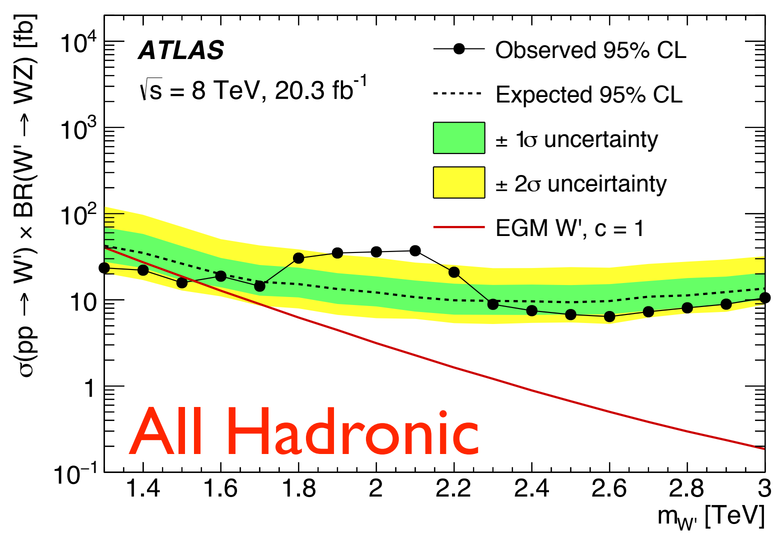


ATLAS, Eur. Phys. J. C (2015) 75:69





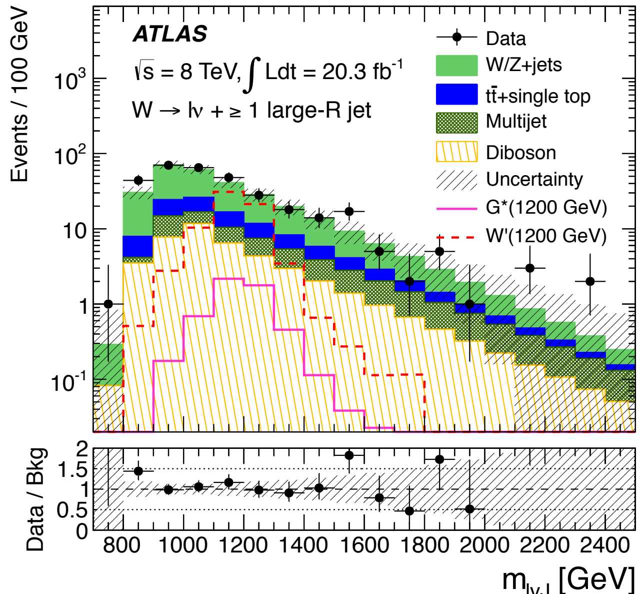
ATLAS, arXiv:1506.00962

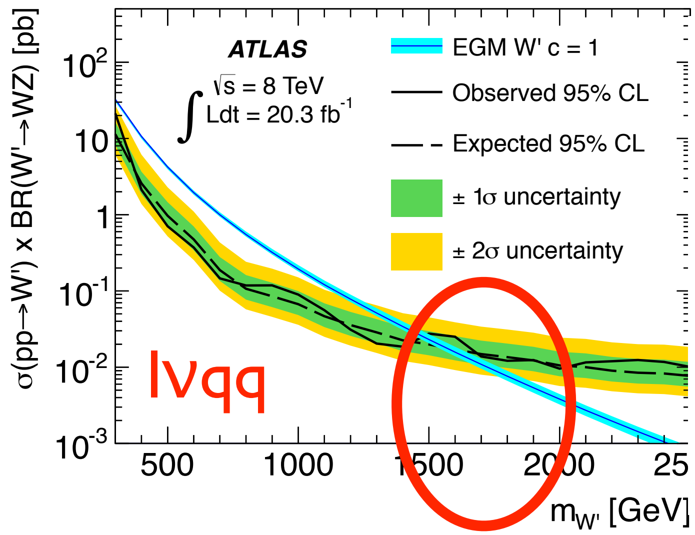


No evidence…

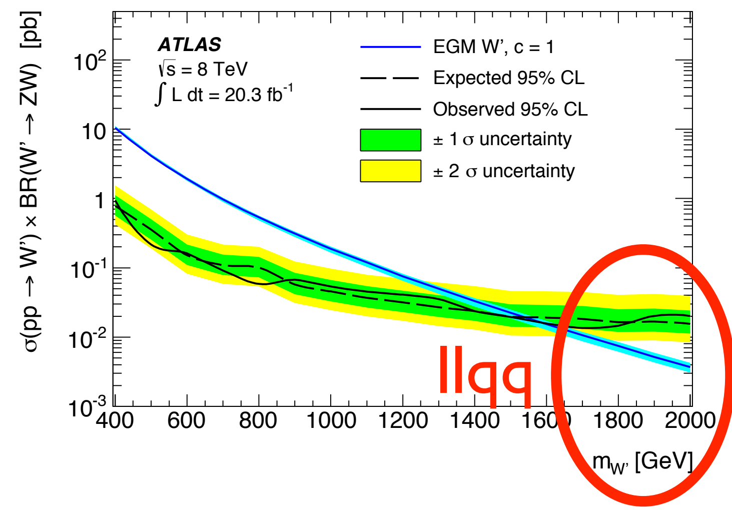
Diboson Resonance Results: ATLAS

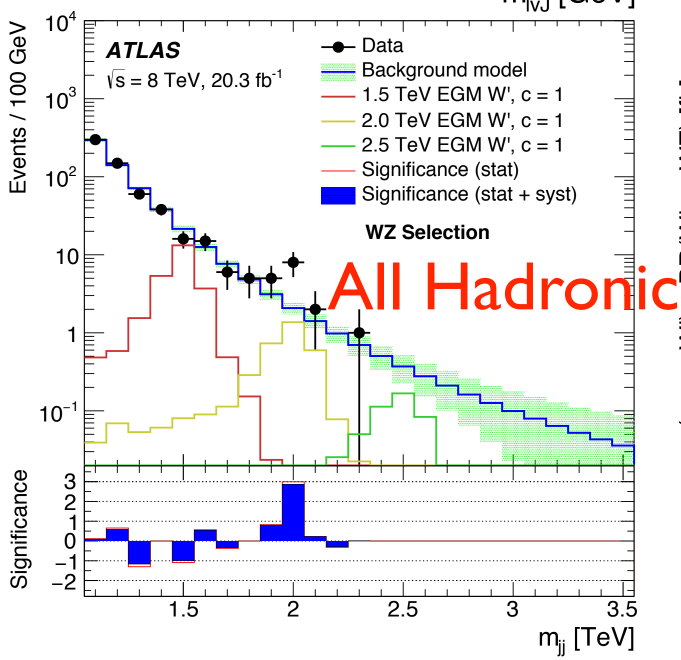
ATLAS, Eur. Phys. J. C (2015) 75:209



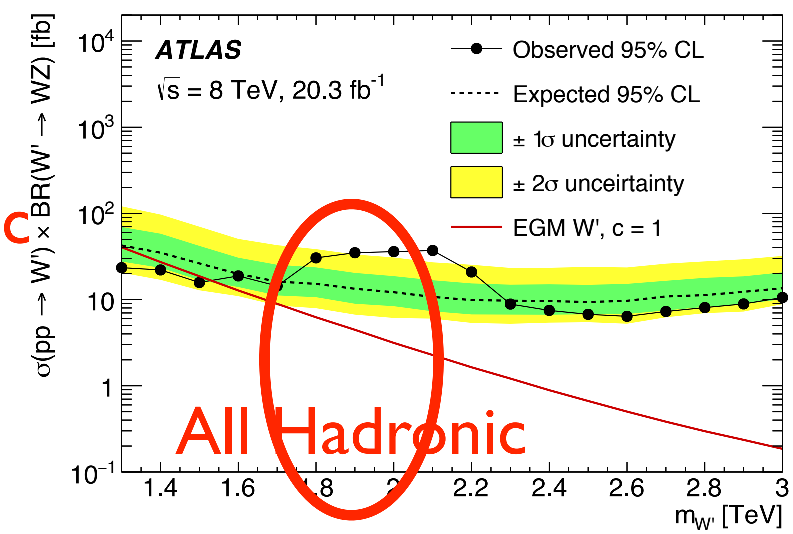


ATLAS, Eur. Phys. J. C (2015) 75:69





ATLAS, arXiv:1506.00962



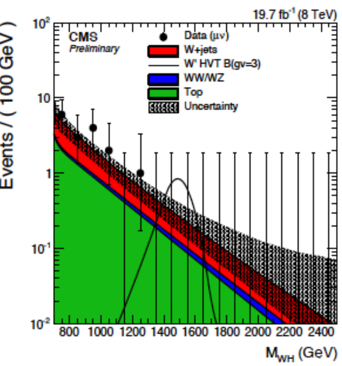
No evidence…

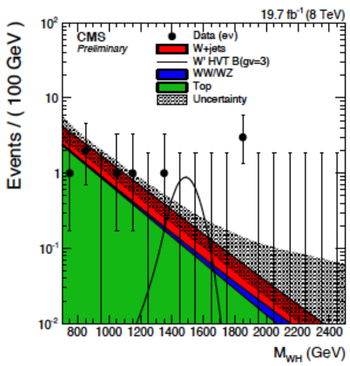
lesser coincidence?

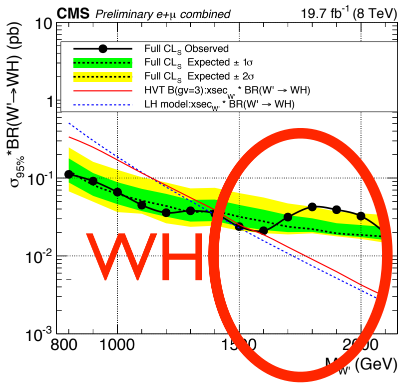
Decays to VH?

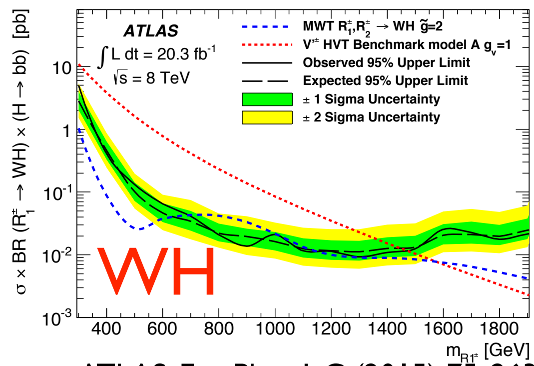
- Both ATLAS & CMS have analyses with b-tags
  ⇒ reduced acceptance

CMS-PAS-EXO-14-010

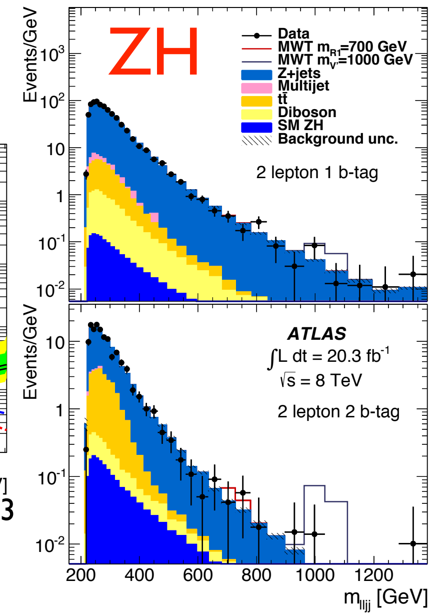






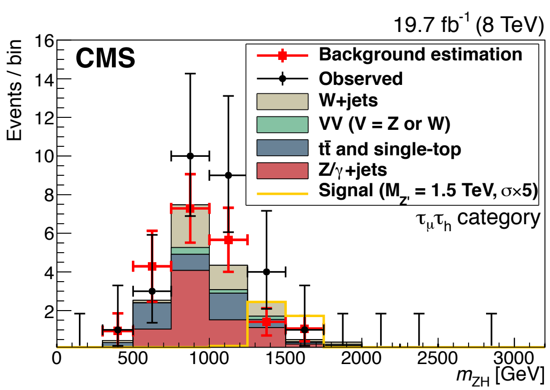


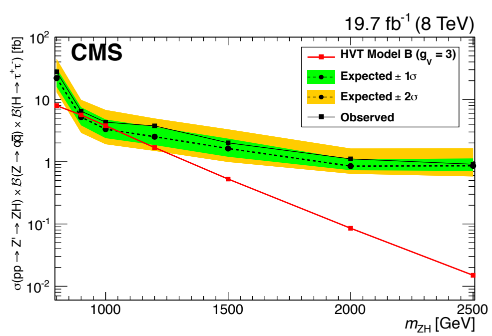
ATLAS, Eur. Phys. J. C (2015) 75: 263



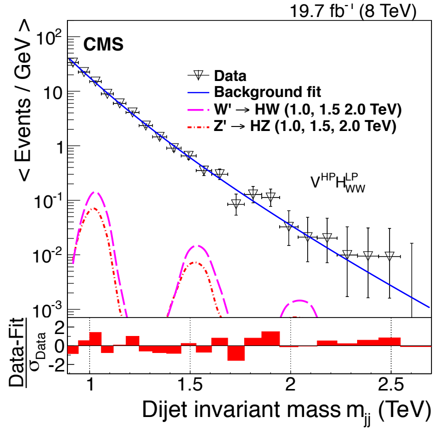
- CMS ZH ⇒ ττJ and all-hadronic VH

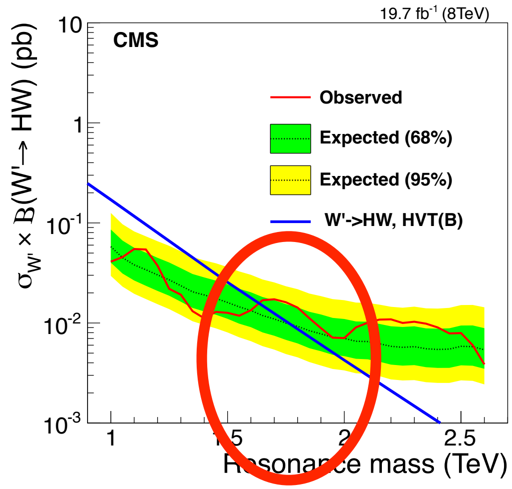
CMS, arXiv:1506.01443





CMS, arXiv:1502.04994

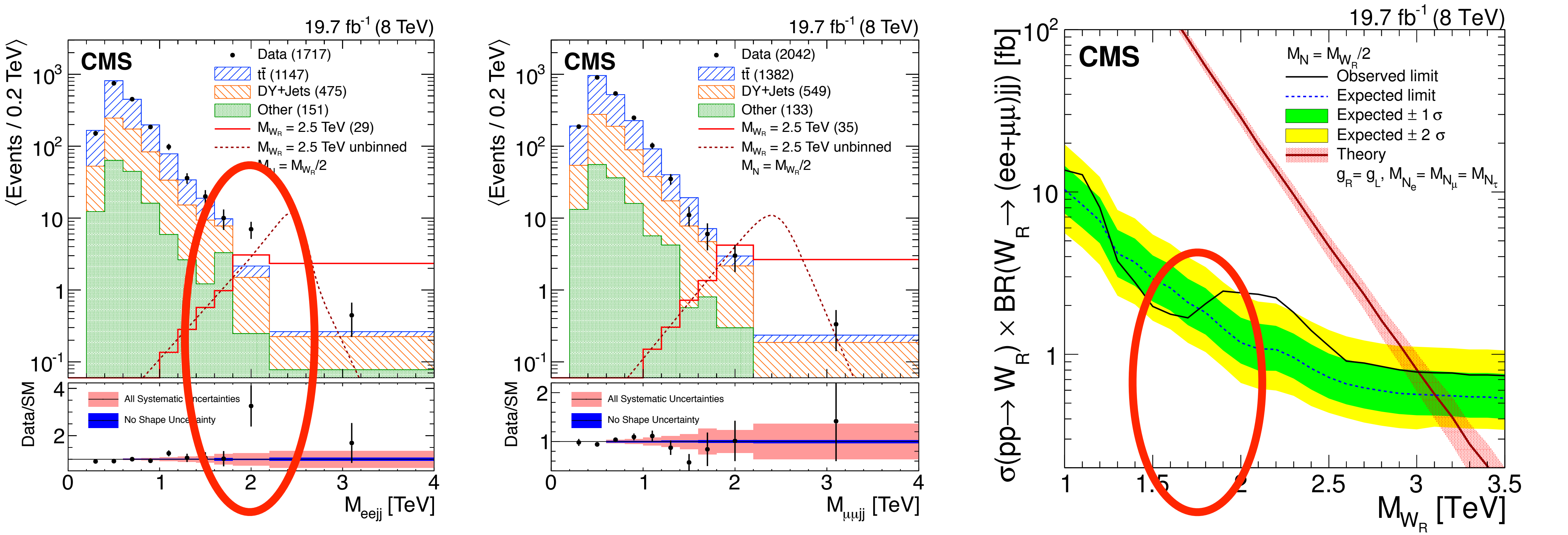




Speculating…

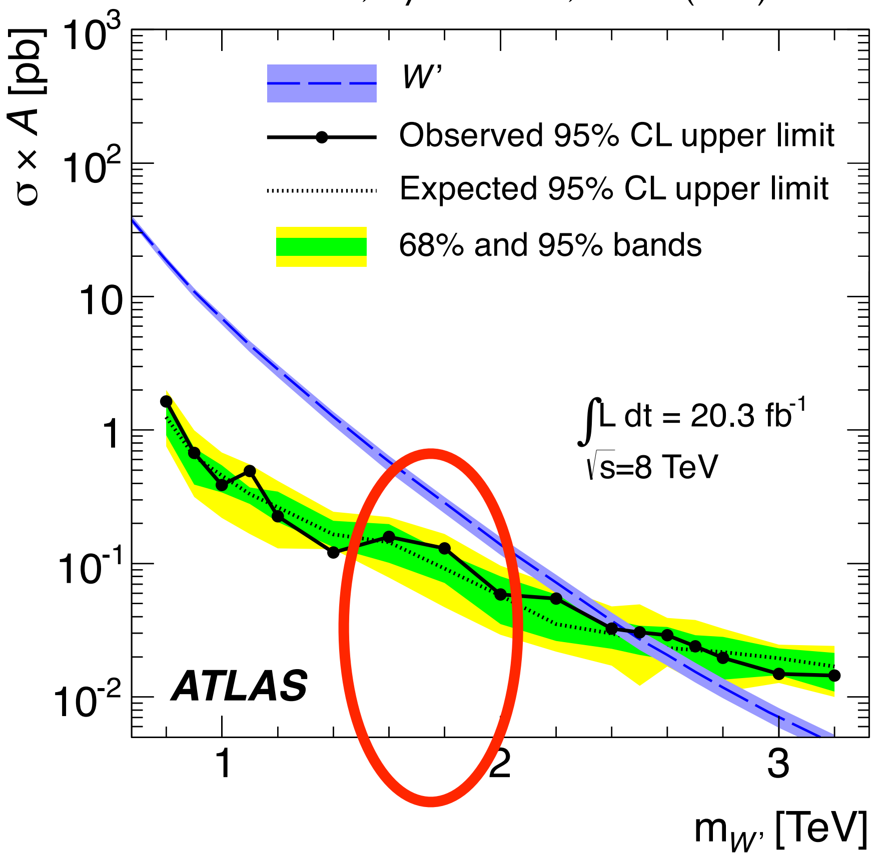
- Hints for a W'?
  - If it's W_R it might decay via ν_R: $W_R \to \ell\nu_R^{(*)} \to \ell(\ell W_R^*) \to \ell(\ell(q\bar{q}'))$
    - Dilepton + two jets final state

CMS, Eur. Phys. J. C 74 (2014) 3149

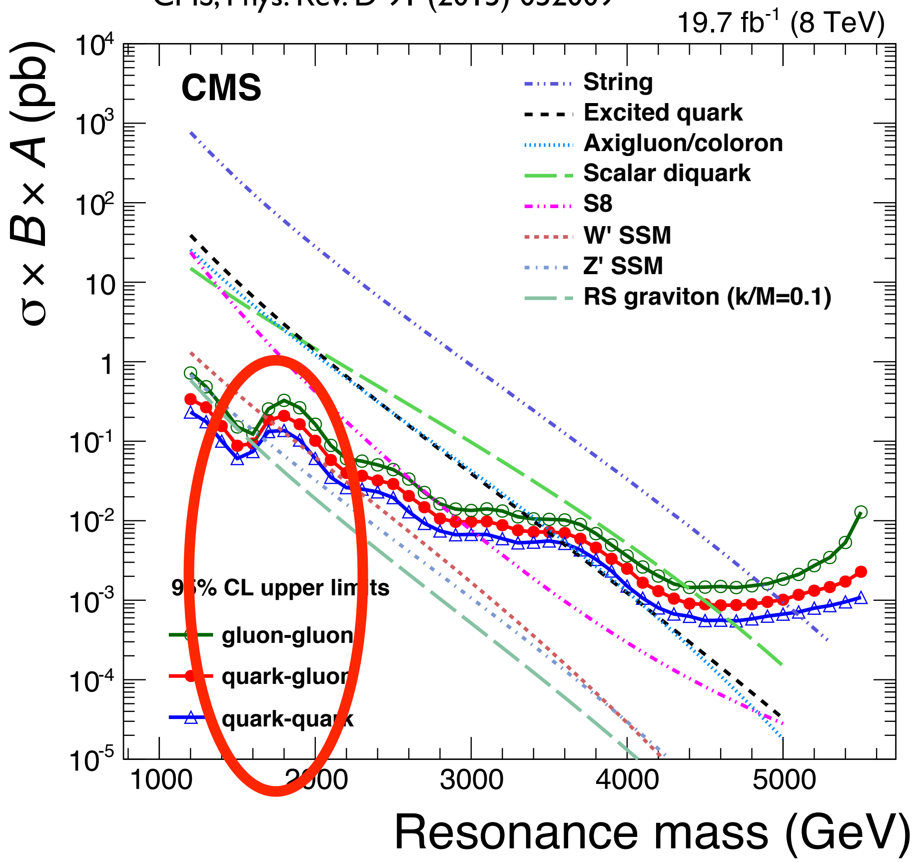


And Dijets

ATLAS, Phys. Rev. D. 91, 052007 (2015)

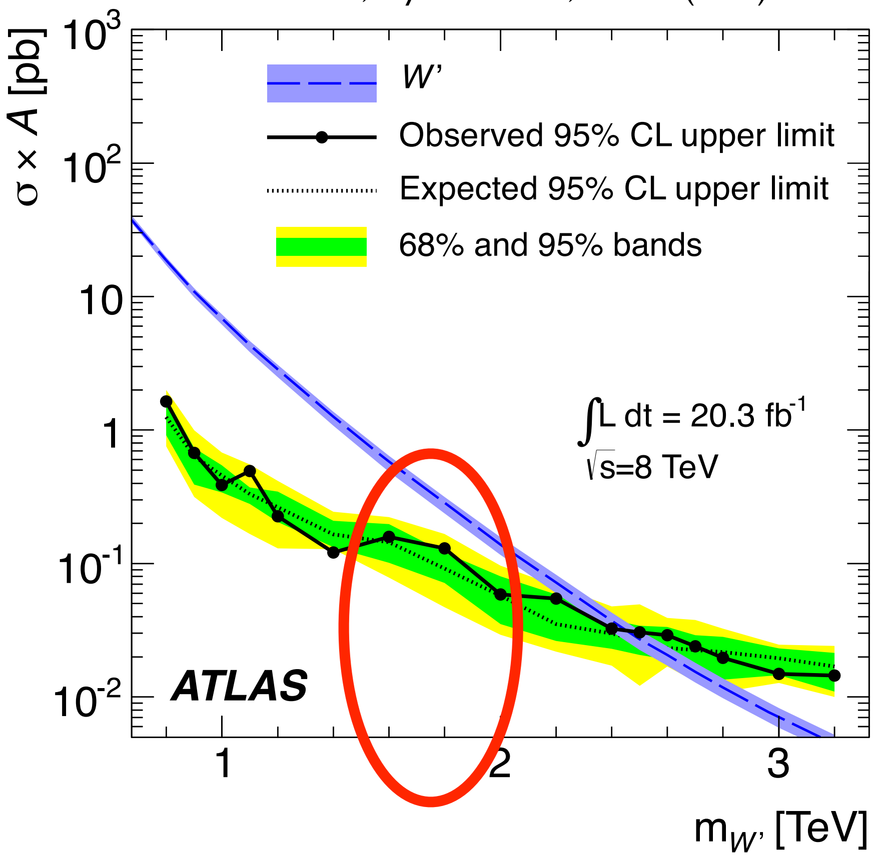


CMS, Phys. Rev. D 91 (2015) 052009

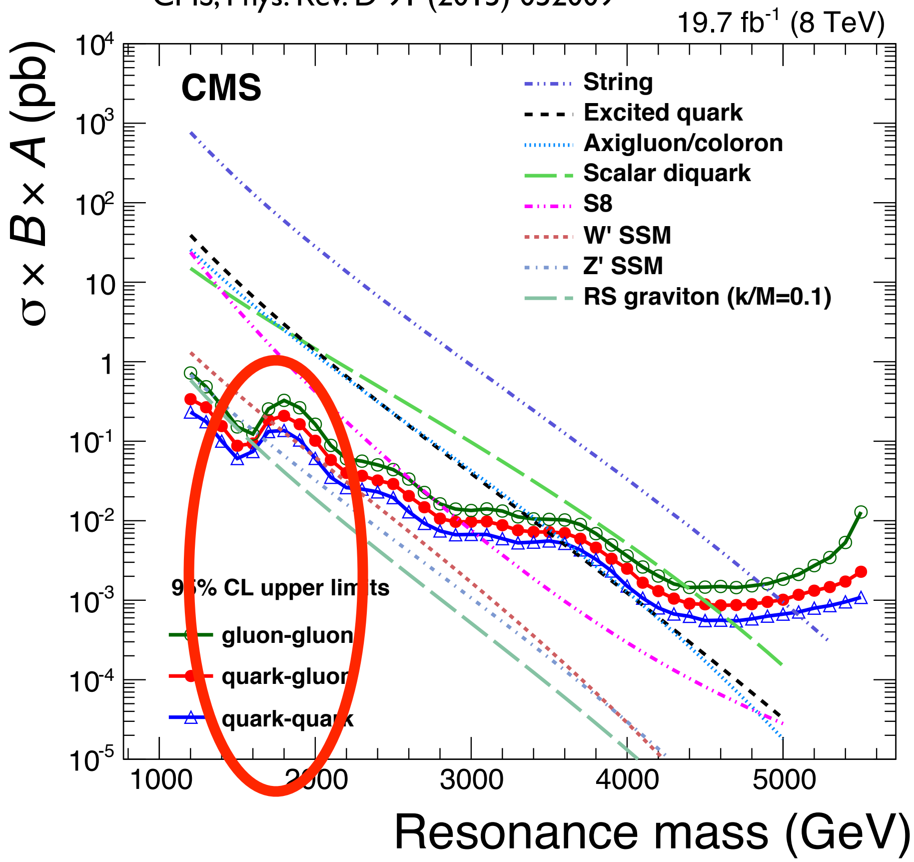


And Dijets

ATLAS, Phys. Rev. D. 91, 052007 (2015)



CMS, Phys. Rev. D 91 (2015) 052009

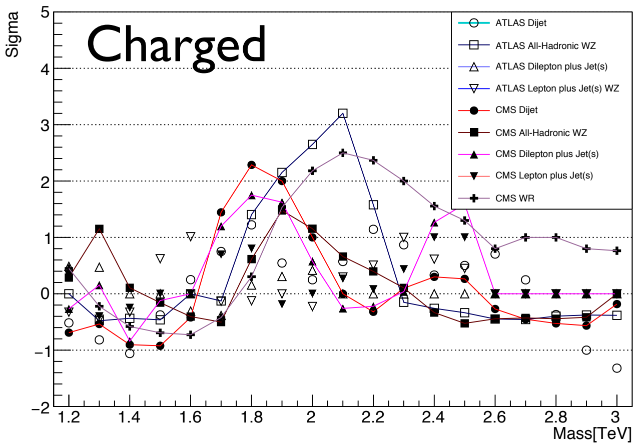


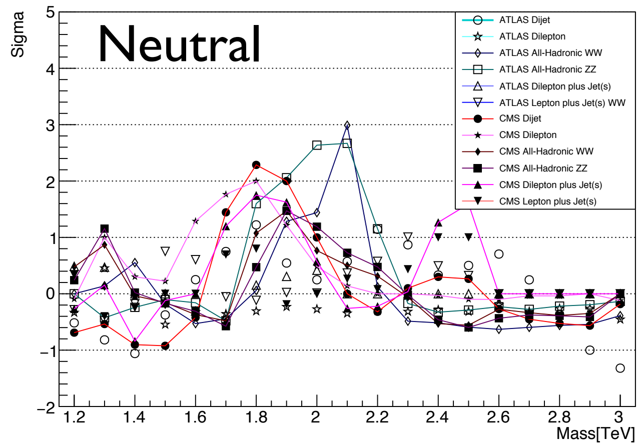
➡ Intriguing number of 1-2 sigma excesses at ~1.9 TeV (mostly at edge of kinematic range):

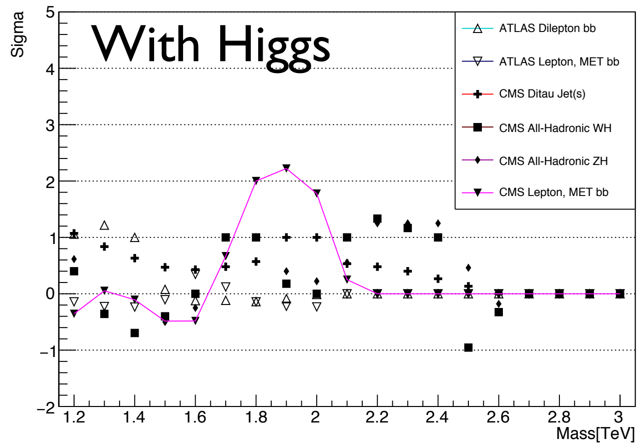
- 2 in ATLAS: all-hadronic diboson, dijet
- 5 in CMS: all-hadronic, llJ, WH diboson, W_R, dijet, dilepton

Comparing Excesses

- Are they all at the same mass?







- Somewhat… needs 2016 data

We Should Have Excesses!

- Run 1:
  - ATLAS: ~50 exotics + ~40 susy papers @ 8 TeV
  - CMS: ~50 exotics + ~25 susy papers @ 8 TeV
  - Expect ~eight false 2σ (excesses+deficits) and maybe one 3σ
- Expect ~four >2σ and 0.25 >3σ accidental excesses
- 3σ:
  - ATLAS Z+MET
- 2+σ:
  - $H \to \mu\tau$
  - ~2 in same-sign dileptons
  - ~4 in W'/Z'-type searches
- Count is ~double…
- … and false positives not expected to cluster…

Thanks

(and mainly: question everything!)